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CENTER FOR SPACE CONSTRUCTION

University of Colorado, Boulder

ANNUAL REPORT

October 1, 1993

CENTER FOR SPACE CONSTRUCTION

University of Colorado at Boulder
Boulder, CO 80309-0529

A NASA University Space Engineering Research Center
Grant NAGW-1388
NASA Program Manager: Robert J. Hayduk
Chair, NASA Technical Review Committee: John Malone

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INTRODUCTION

Renjeng Su, Director

The Center for Space Construction (CSC) at the University of Colorado at Boulder is one of eight University Space Engineering Research Centers established by NASA in 1988. The mission of the Center is to conduct research into space technology and to directly contribute to space engineering education. The Center reports to the Department of Aerospace Engineering Sciences and resides in the College of Engineering and Applied Science. The College has a long and successful track record of cultivating multi-disciplinary research and education programs. The Center for Space Construction is prominent evidence of this record.

At the inception of CSC, the Center was primarily founded on the need for research on in-space construction of large space systems like space stations and interplanetary space vehicles. The scope of CSC's research has now evolved to include the design and construction of all spacecraft, large and small. Within this broadened scope, our research projects seek to impact the underlying technological basis for such spacecraft as remote sensing satellites, communication satellites and other special-purpose spacecraft, as well as the technological basis for large space platforms.

The Center's research focuses on three areas: a) spacecraft structures, b) spacecraft operations and control, and c) regolith and surface systems. In the area of spacecraft structures, our current emphasis is on concepts and modeling of deployable structures, analysis of inflatable structures, structural damage detection algorithms, and composite materials for lightweight structures.

In the area of spacecraft operations and control, we are continuing our previous efforts in process control of in-orbit structural assembly. In addition, we have begun two new efforts in a) formal approach to spacecraft flight software systems design and b) adaptive attitude control systems. In the area of regolith and surface systems, we are continuing the work of characterizing the physical properties of lunar regolith, and we are at work on a project on path planning for planetary surface rovers.

The Center has completed a number of laboratory facilities. There is a sophisticated structural testing lab which is jointly funded by the Center and other funding sources. There is an air-bearing facility for small-scale motion and control study in two dimensions. There is a rover testbed for the study of hierarchical and modular software systems for remote control. We have also completed several testbeds for the study of regolith characterization and mechanical penetration tools.

In the past year the Center made a decision to propose in-space experiments. Our efforts in this direction have been successful in winning two Phase-A NASA In-Space Technology Experiment Program (In-STEP) projects. The Micron Accuracy Deployment Experiment (MADE) will test and verify a concept for precision deployable antennas. The Modular Isolation Microgravity Experiment (MIME) will test and verify various passive and active control technologies to achieve microgravity isolation for a modular platform.

Our education program has primarily focused on graduate teaching, and in the past year we graduated four Doctoral and nine Masters students. During the same period six undergraduates were associated with the Center; we shall continue to increase undergraduate students' participation in our programs. Meanwhile, we are vigorously attempting to more formally increase our impact on undergraduate education: last summer CSC completed a proposal for a two-semester undergraduate interdisciplinary spacecraft design course.

RESEARCH PROGRESS

ORBITAL SYSTEMS

A NEW DESIGN CONCEPT FOR HIGH-PRECISION DEPLOYABLE REFLECTORS

Martin M. Mikulas, Jr., Lee D. Peterson, Peter Withnell

Autonomously deployment of precision reflectors on orbit is important for scientific and defense applications. The reliability of both the deployment process and the reflector operation is of primary importance. CSC, in collaboration with NASA Langley Research Center, has been awarded Phase A funding for a flight experiment designed to research both these areas, entitled Micron Accuracy Deployment Experiment (MADE). If funded to completion, MADE will deploy a five-meter diameter reflector able to operate at wavelengths as low as 50 microns.

In order to meet the goals of autonomous and reliable deployment and operation, CSC has devised several structural concepts, and initiated work on their designs. In CSC's primary structural concept, a linkage deploys the panels from their stowed positions directly into their deployed configuration in a single degree-of-freedom motion. The simplicity of this mechanism improves deployment reliability. The goals of autonomy and reliability also affected our design of the support structure, which we designed to deploy synchronously, so that it would relatively easily accomodate redundant actuator systems. The support structure also includes three circumferential preload members, which provide the structural preload necessary to remove intrinsic joint freeplay. This preload force biases the joints and hinges to remain in one position, thus providing a positionally stable support to which the reflector segments may be attached. Material variability and manufacturing tolerances limit the surface accuracy to approximately 50 microns.

This highly precise surface accuracy requires a new paradigm of construction techniques. MADE will be the first example of adaptive sensing and actuation to improve construction reliability. Each panel includes sets of actuators enabling micron adjustment in three degrees of freedom. A surface metering system will then quantify the surface errors and feed the information back to the surface control actuators. Using this technology, MADE promises to achieve a surface accuracy five times higher than that of other deployable reflector designs—a level which until now only erectable structures such as those represented by the NASA-Langley PSR Project have achieved.

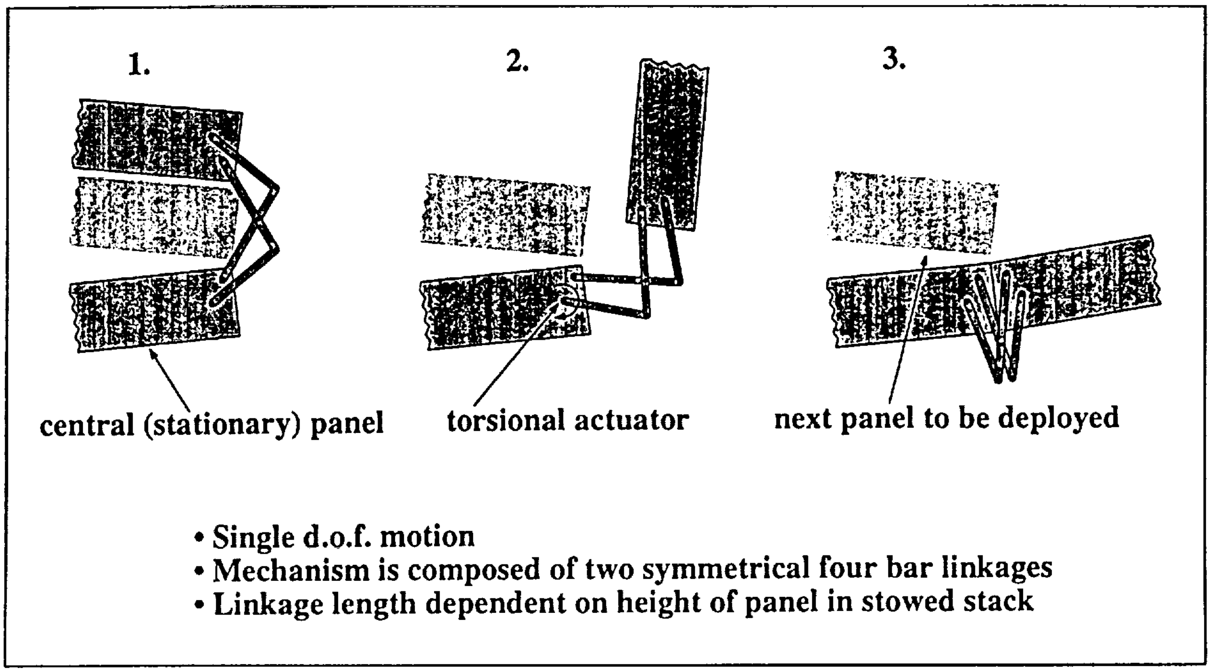


Figure 1.1 Panel deployment mechanism

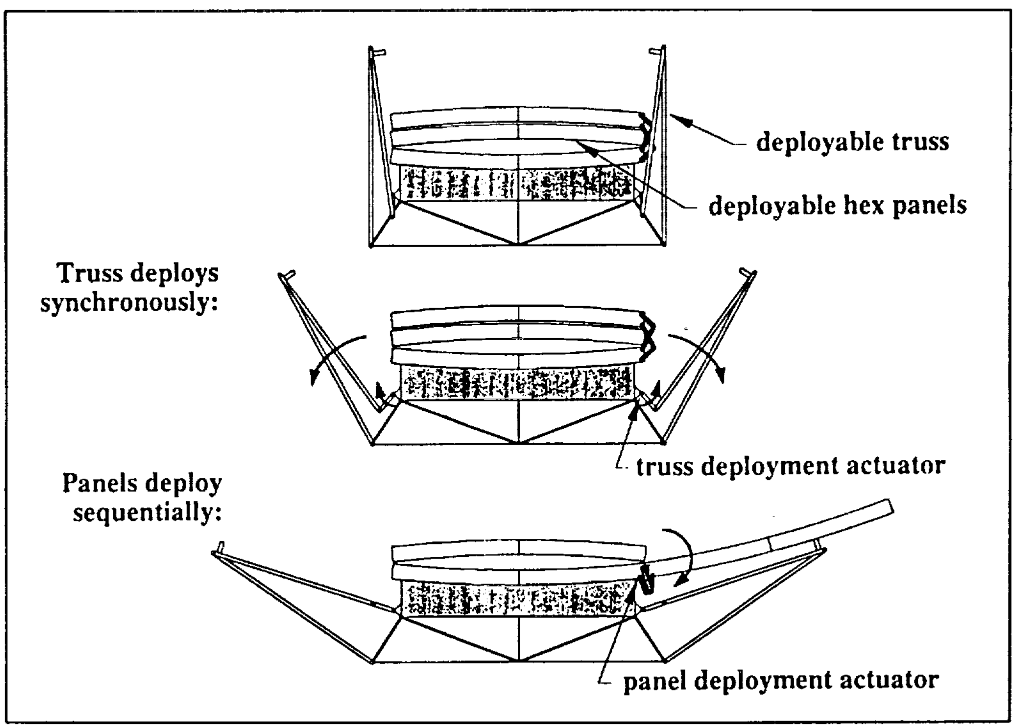


Figure 1.2 Deployment of MADE

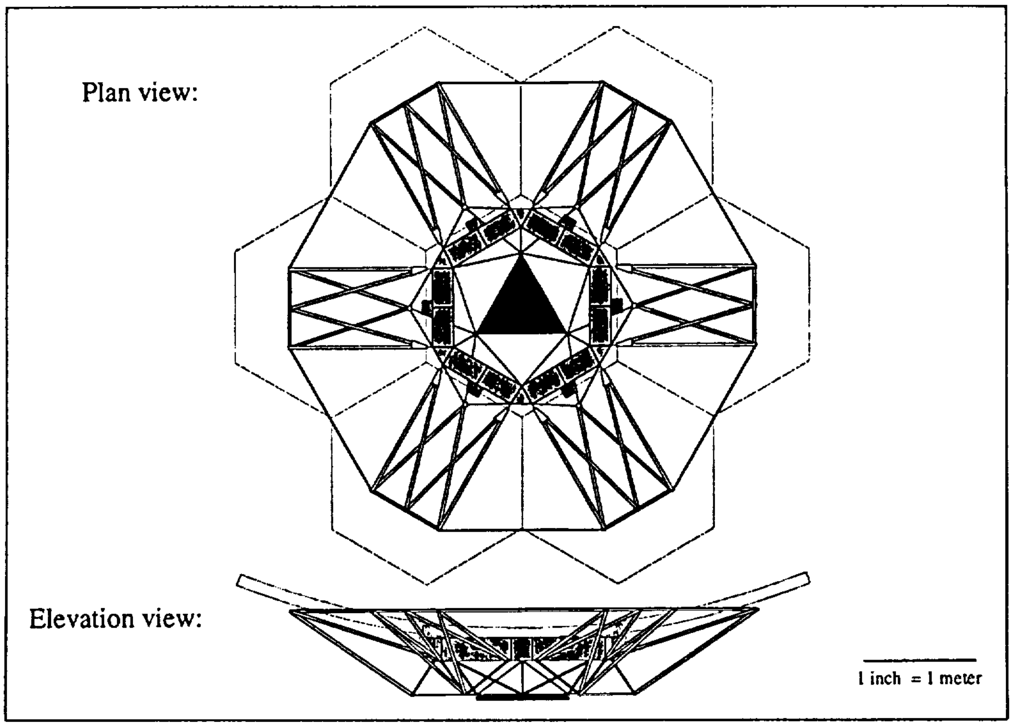


Figure 1.3 Plan and elevation views of MADE

POTENTIAL DEPLOYED REFLECTOR AREA FOR VARIOUS DEPLOYMENT CONCEPTS

Peter Withnell, Martin M. Mikulas, Jr.

Packaging efficiency and deployment complexity are two important factors in deployable reflector concepts. The ability to maximize packaging efficiency while maintaining simplicity in deployment mechanisms is becoming increasingly more important to the scientific community. This study presents new concepts designed by CSC to meet these goals. Each concept uses four single-degree-of-freedom mechanisms to deploy the reflectors, which are composed of only three panels. In order to compare these new concepts with established designs, CSC has produced a chart based on the area expansion ratio—defined as the ratio between the reflector surface area and the area of the circular cross-section of the launch shroud—to quantify the packaging efficiency of each concept.

We explored two basic orientations. First, the panels may be stacked laterally, where their surfaces are parallel to the launch shroud's circular cross-section. The effect of introducing chamfered corners on each panel is also studied. This concept yields area expansion ratios around 2. The second package orientation examined is longitudinal, where the panels lie within the launch shroud so that the surfaces are perpendicular to the shroud's circular cross-section. By locating the pivots so that the packaging efficiency is maximized, the area expansion ratio is approximately 5, and little difference is found between spherical and parabolic reflectors.

The chart in Figure 2.1 compares these two new concepts with six established designs. The least complex of all eight is the *monolithic* design, composed of a single panel, with an area ratio of one. Using several panels, larger reflectors can be constructed, such as a *single ring* reflector, which can be constructed from hexagonal panels (7 panels) or a higher number of wedge-shaped panels surrounding a polygonal center panel (12 wedges surrounding a 12 sided interior panel, for example). Using multiple hexagonal panels, *hex arrays* can also be formed by lining up the panels in an oblong matrix. *Petal reflectors* are another example of how multiple panels may be used, where each panel deploys from a cylindrical package to form the reflector, the way a flower's petals unfold. Typically these reflectors use between 20 and 30 panels. are also included on the chart. The extremely high packaging efficiency of *inflatable* reflectors results in area ratios on the order of 1000.

This study has noted a general trend in which reflectors composed of a high number of panels typically have higher packaging efficiencies than those which contain fewer panels, but also appear to have higher deployment complexity. The study provides quantitative comparisons between vastly different reflector concepts, and demonstrates that designs employing only minimally complex mechanisms can produce viable reflectors with competitive area expansion ratios.

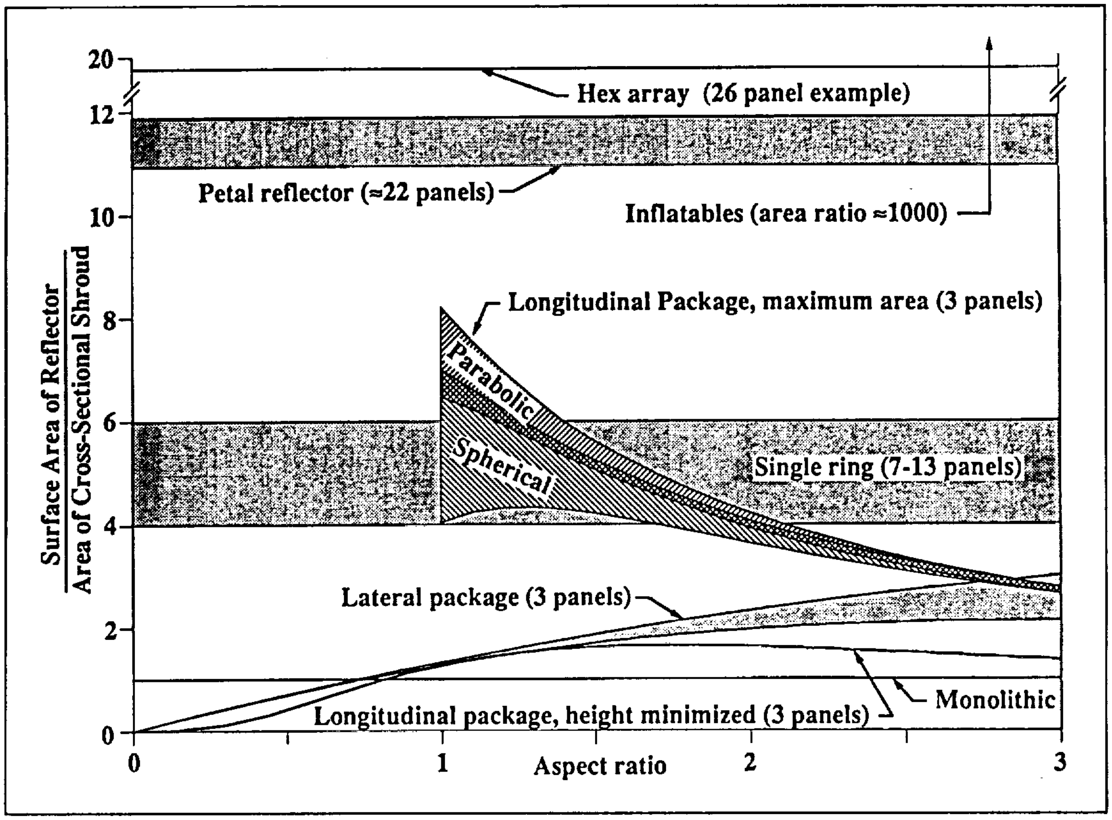
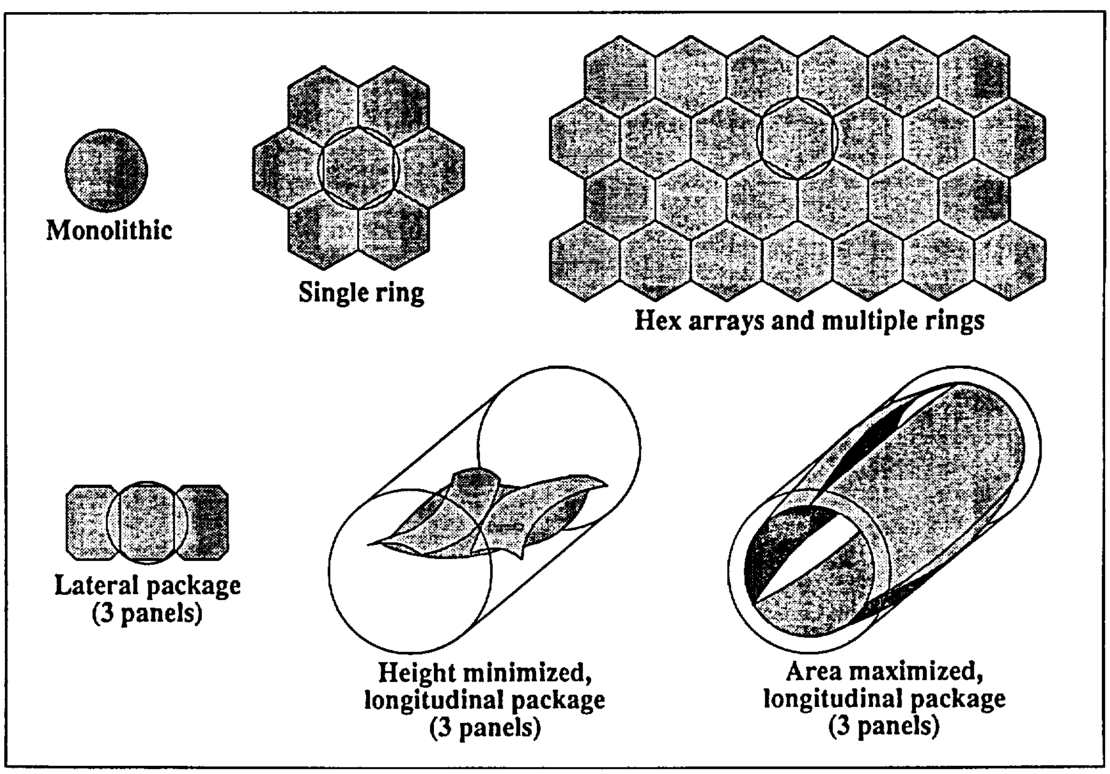


Figure 2.1 Achievable surface areas for space-based reflectors deployed from a cylindrical shroud



Figuure 2.2 Deployable reflector concepts

AN ELECTROMAGNETIC PATTERN SIMULATOR FOR HEXAGONAL DEPLOYABLE ANTENNAS

Paul Labys, Noureddine Kermiche, Renjeng Su

One of the major research interests of the Center for Space Construction is high-precision deployable antennas. The MADE concept now under study is a mechanically deployable antenna that consists of a strut structure and a set of hexagonal panels. These hexagonal panels form a parabolic reflecting surface the precision of which is mainly achieved by the supporting struts. Our target surface precision for such antennas is at the order of 50 microns RMS, which presents a great challenge for design as well as shape control during operations.

To this end we have developed a simple computer program that simulates the electromagnetic radiation pattern of such a deployable antenna. The antenna surface is composed of hexagonal panels. The user can introduce small tilt errors in the reflector panels, similar to those that might be caused by heat distortions in orbit or errors in deployment. The program calculates the electromagnetic pattern of the distorted antenna.

The program was developed using the commercially available software program MATLAB[R]. On a SUN Sparc 2 workstation, single runs for a seven-panel parabolic antenna take less than five minutes.

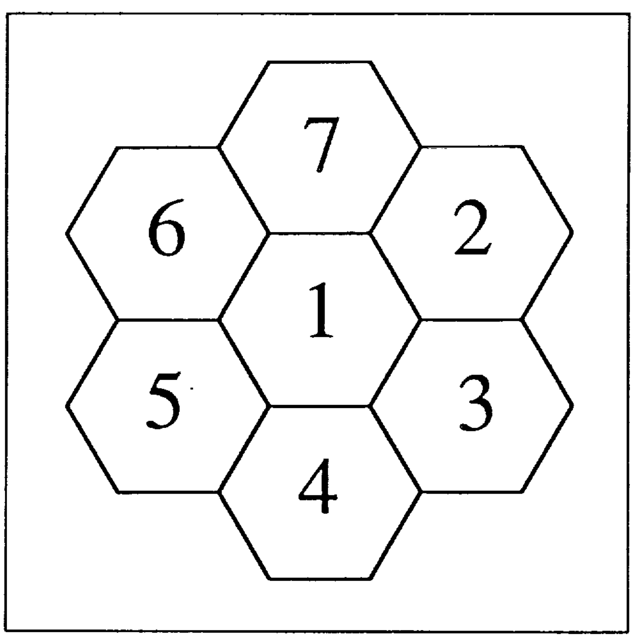


Figure 3.1 Parabolic hexagonal antenna (top view)

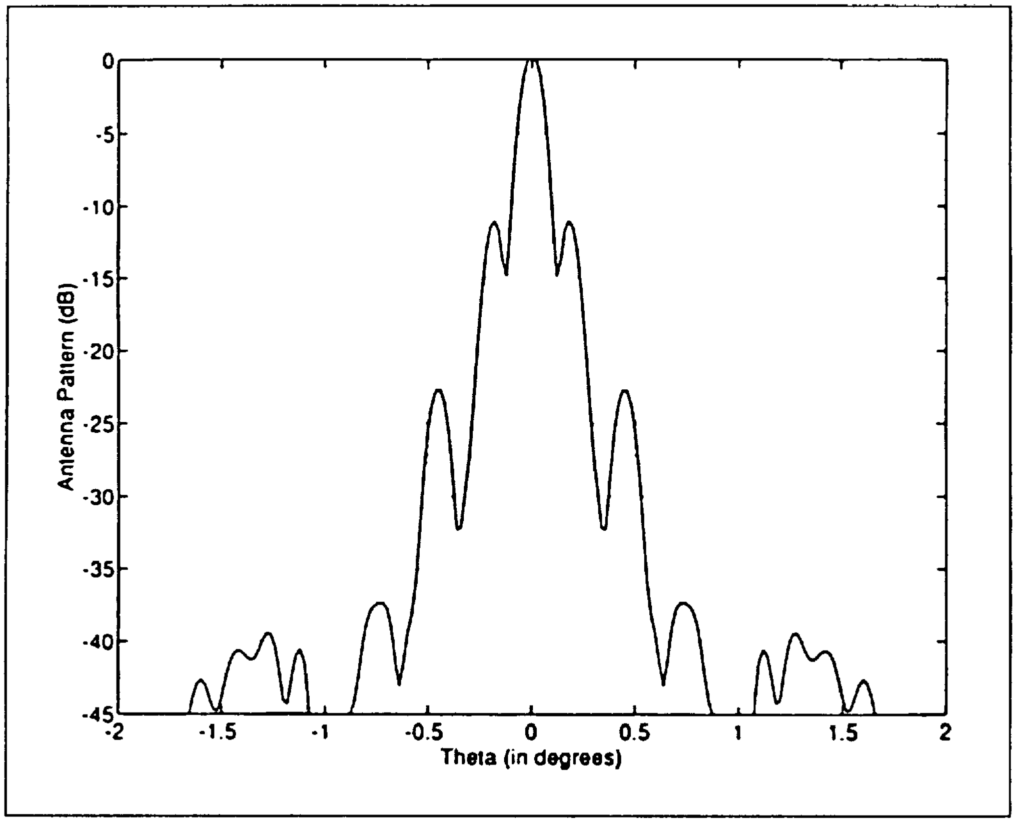


Figure 3.2 EM antenna pattern for standard configuration, no errors

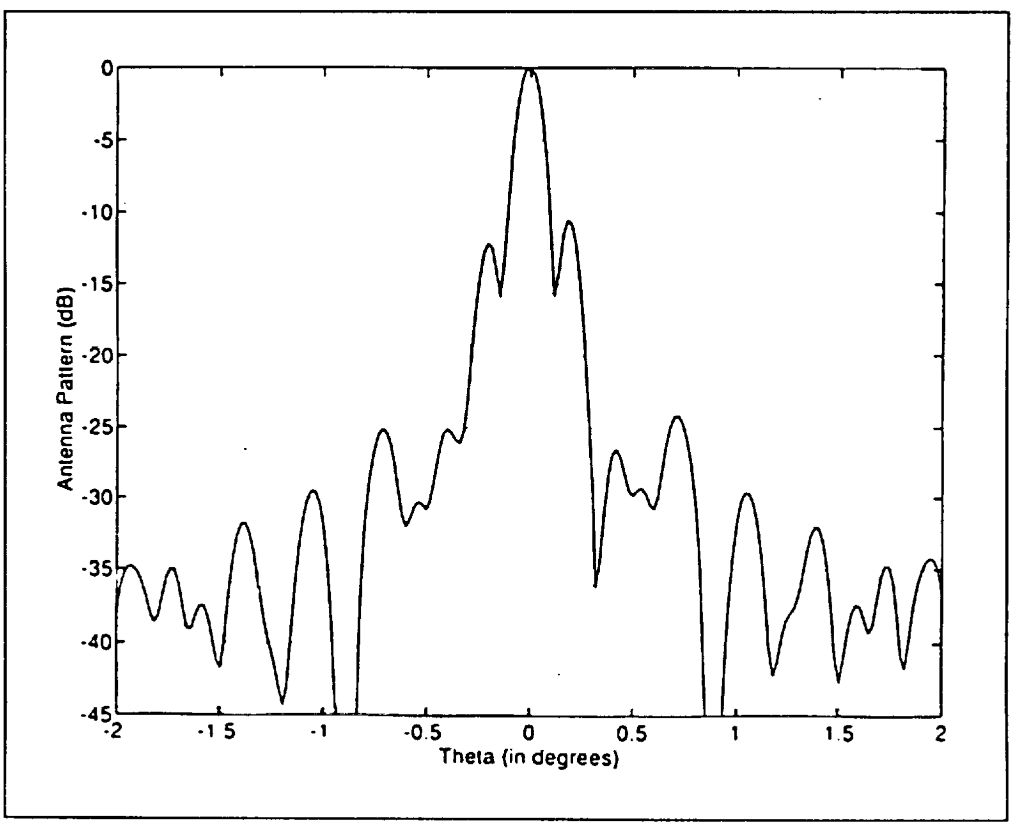


Figure 3.3 EM pattern for Beta error .02 2nd panel, Phi=1 degree

A STRUCTURAL DESIGN METHODOLOGY FOR LARGE-ANGLE ARTICULATED TRUSSES WITH REALISTIC JOINT EFFECTS

Gregory Thorwald, Martin Mikulas Jr.

This research has developed a structural design methodology by quantifying the magnitude of the adverse affect that large-angle articulations and realistic modeling considerations have on the structural stiffness of a truss. We first identified and examined geometry and modeling considerations, and next developed and evaluated design strategies to alleviate stiffness reduction for the truss. Finally we developed and have demonstrated a new articulated truss.

The new articulated truss incorporates the design modifications including an initially curved deployed configuration to improve the articulation performance of the truss. The truss uses length actuators in the batten locations, as the batten members are not in the primary load path. The batten actuators are able to both deploy the truss and provide large-angle articulation.

An idealized truss model with simple point-to-point member connections was compared to a realistic truss model. The realistic truss model includes the offset distances to the hinges. These are necessary for correctly packaged geometry. Non-structural mass is added to both models.

Analysis results show two causes of structural stiffness reduction for an articulated truss. The first (which affects both truss models) is due to the large angle articulated geometry of the truss, where the effective overall bending stiffness (EI) is reduced due to short battens. The second cause is observed in the realistic truss model. Local bending moments are applied to the battens during articulation due to the hinge offset lengths. The batten member bending further reduces the truss stiffness, compared to the idealized truss. Figure 4.1 illustrates the stiffness reduction mechanisms. Figure 4.2 gives a stiffness trend comparison between the ideal and realistic truss models, for the articulated truss using one batten actuator.

Alleviating a the stiffness reduction of a truss has a dual purpose: first, to improve the structural performance; and second, to verify the cause of the stiffness reduction. Strategies to remedy the stiffness reduction due to local batten bending include increasing the batten's bending inertia and modifying the hinge offset lengths to improve the offset truss's stiffness compared to the ideal truss. Distributing the actuation, increasing the truss height, increasing the amount of material in the truss members, and designing the truss's nominal configuration to be initially curved within the operational area are geometric strategies to increase the truss's overall stiffness for articulated configurations.

Initial results for three of the stiffness improvement strategies show that distributing the actuation, increasing the batten's bending inertia, and modifying the hinge offset lengths have helped to alleviate the truss's stiffness reduction. The other strategies will be evaluated to determine the amount by which they alleviate the stiffness reduction.

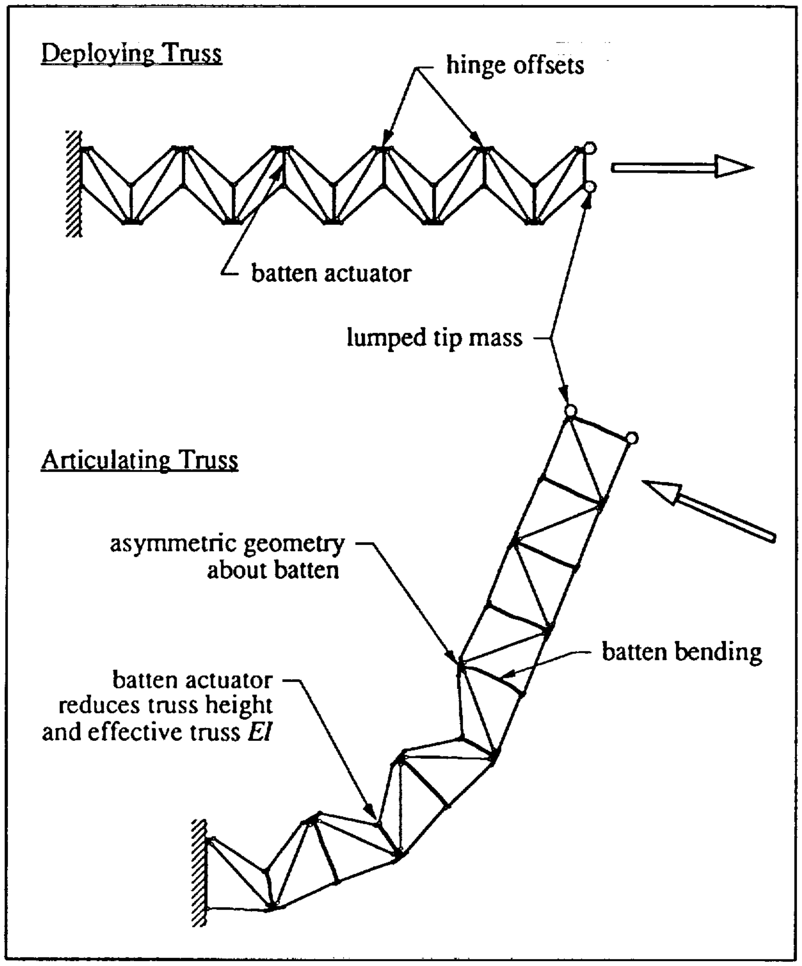


Figure 4.1 Stiffness reduction mechanisms for articulated trusses

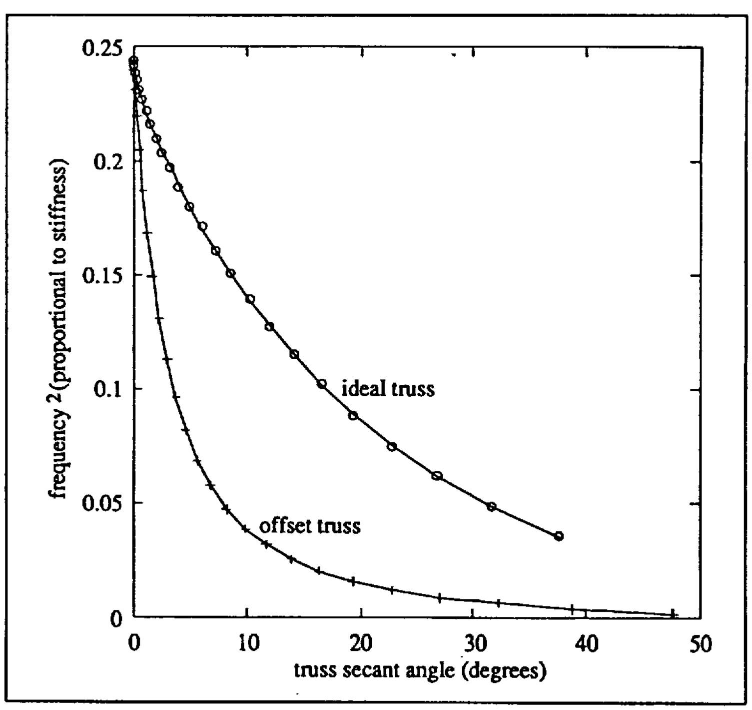


Figure 4.2 Truss stiffness trend using a single actuator

CONCEPTUAL DESIGN AND KINEMATIC ANALYSIS OF AN UNFURLABLE HELICAL BEAM STRUCTURE

K.C. Park, Gyula Greschik

Deployable booms have been in use for space structural components for over three decades. Typically the existing boom designs are of three types: deployable truss beam with attendant joints, straight unfurlable boom, and continuously deployable boom with cross-sectional stabilizers. From a stiffness viewpoint, jointed truss beams are the most desirable; however, they suffer from weight penalty due to the use of joints and deployment mechanisms. Continuously deployable three-longeron booms have been in great demand; however, as the boom length increases the torsional stiffness becomes problematic for many intended space missions. Finally, unfurlable straight booms are easy to deploy, with, perhaps, a minimum weight penalty. For general applications, however, it is necessary to strengthen both their bending and their torsional stiffness.

These facts have led us to explore an alternative design of booms, one which does not require joints, which is continuously deployable and retractable, and which has superior bending and torsional stiffness properties over straight unfurlable booms. From several possiblilities, we have chosen to design an unfurlable tubular helical beam.

Our proposed concept for an unfurlable helical beam involves a non-cylindrical drum onto which the tubular beam's constituent plate, opened up along its length to form a strip, is rolled. Proper design of the drum's profile assures that the retracted strip experiences bending but no membrane shell strains with respect to its deployed configuration. The primary design problem is to determine the drum profile, which satisfies this criterion for a particular helical tube geometry and drum radius. This, as well as the calculation of the shell bending strains, is based on the analysis of the kinematics of the mechanism.

Figure 5.1 shows the unfurling concept proposed for helical tubes in comparison to that applied for straight ones. The drum profiles for an example model where the helical tube is cut open along its outermost generator are shown in Figure 5.2. For this model, the radius of the tube cross-section is 2 cm, and the tube centerline helical radius and the ascent of the tube in one full cycle are both 10 cm. Profiles are shown for a number or drum radii in which a correspondence between the drum axis and the horizontal axis of the plots renders each profile curve in the position it would assume on the drum itself.

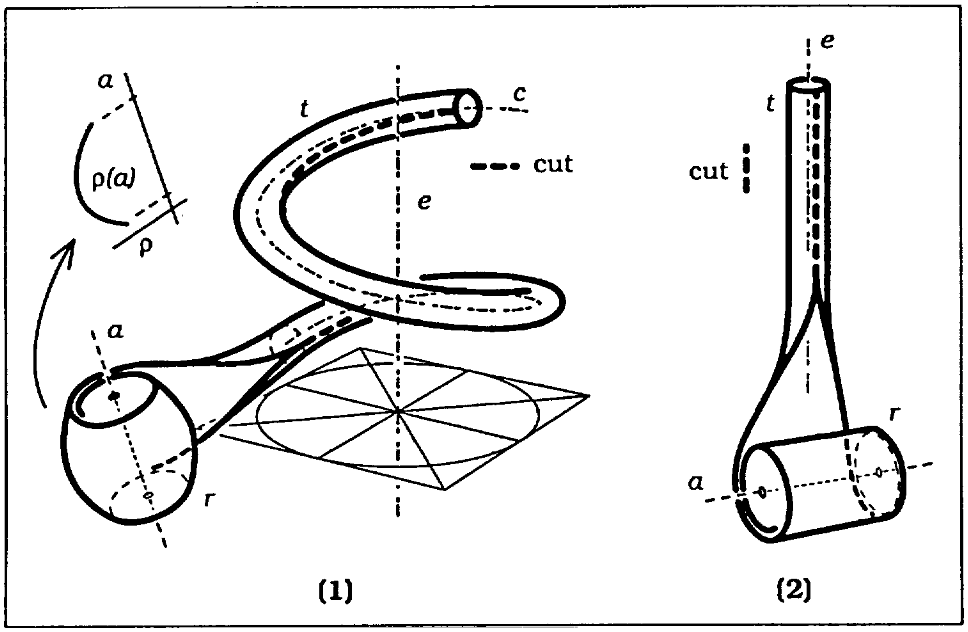


Figure 5.1 Unfurling of a helical tube (1) vs. unfurling of a straight tube (2)

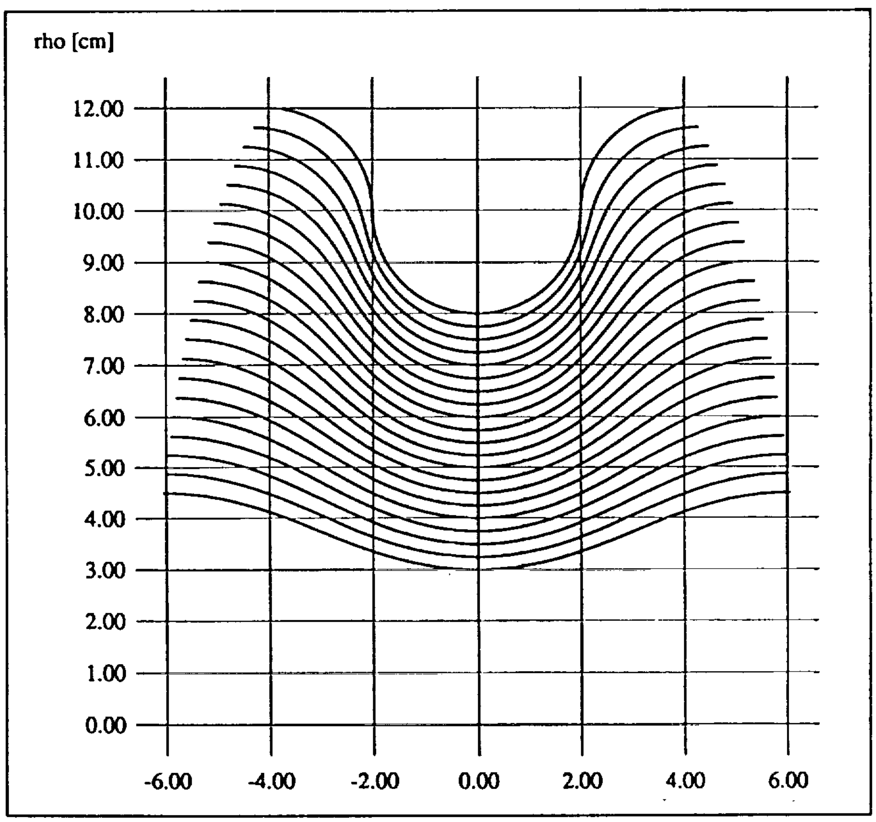


Figure 5.2 Calculated drum profiles for an example problem

CONTACT/IMPACT EXTENSION OF THE PROGRAM MBD3D

K.C. Park, Gyula Greschik

The sensitivity of typical space structures to contact/impact (CI) due to their high flexibility and lack of damping, as well as the inability of most multibody dynamics programs to properly address CI phenomena, prompted us to embark on the development of a high-accuracy multibody dynamics program for modeling impact. The Center for Space Construction, working jointly with the the University of Colorado's Center for Aerospace Structures, decided to enhance an existing multibody dynamics code, MBD3D, to allow it to model CI.

MBD3D, because of some unique computational features it possesses, was a desirable candidate for further development. In particular, the method of constraint enforcement—the modeling of the motion of structural components while accurately retaining their relative position—followed in MBD3D is based on the coupled application of an implicit integrator for the constraint forces and an explicit integrator for the structure's displacement degrees of freedom. This method provides more accurate results than do other methods currently known. Further, in addition to rigid bodies, MBD3D also supports 2-node beam finite elements especially formulated for multibody dynamics applications.

Since September 1992, we have developed a new version of MBD3D which differs from the old one in both its computational and its interactive features. The code has been equipped with the capability to model elastic impact and contact between connected elements---i.e., CI internal to joints---through the combined application of the penalty method and the high-accuracy constraint enforcement algorithm employed for regular constraints. The penalty method is used to model impact (the short duration interpenetration of structural elements) while contact (the steady support between elements touching one another) is treated like a structural joint. Parameters set up by the user can transform impact into contact and vice versa, as dictated by the motion of the model.

These computational features are embedded in a user-friendly software environment which facilitates numerical experimentation via the support of restart and of the run-time modification of analysis parameters. We have also developed a non-graphical postprocessor for the tabular output of a variety of responses. MBD3D is supplied with a printed manual also available on-line, and it is ready for use by the general engineering and research community.

Future development is planned along two lines. First, the code will be continuously improved as dictated by evolving demands for its use. We have already begun to apply it to the deployment of inflatable structures. Second, in the long run we will further extend MBD3D with features which include the capability to model CI between general, non-connected, structural elements. We also plan to extend the variety of responses which its postprocessor can address.

Figure 6.1 shows the TOPEX satellite in deployed position. The deployment of the two-member antenna perpendicular to the solar array has been modelled with MBD3D. Figure 6.2 shows the variation of the angle between the two members of the antenna during deployment.

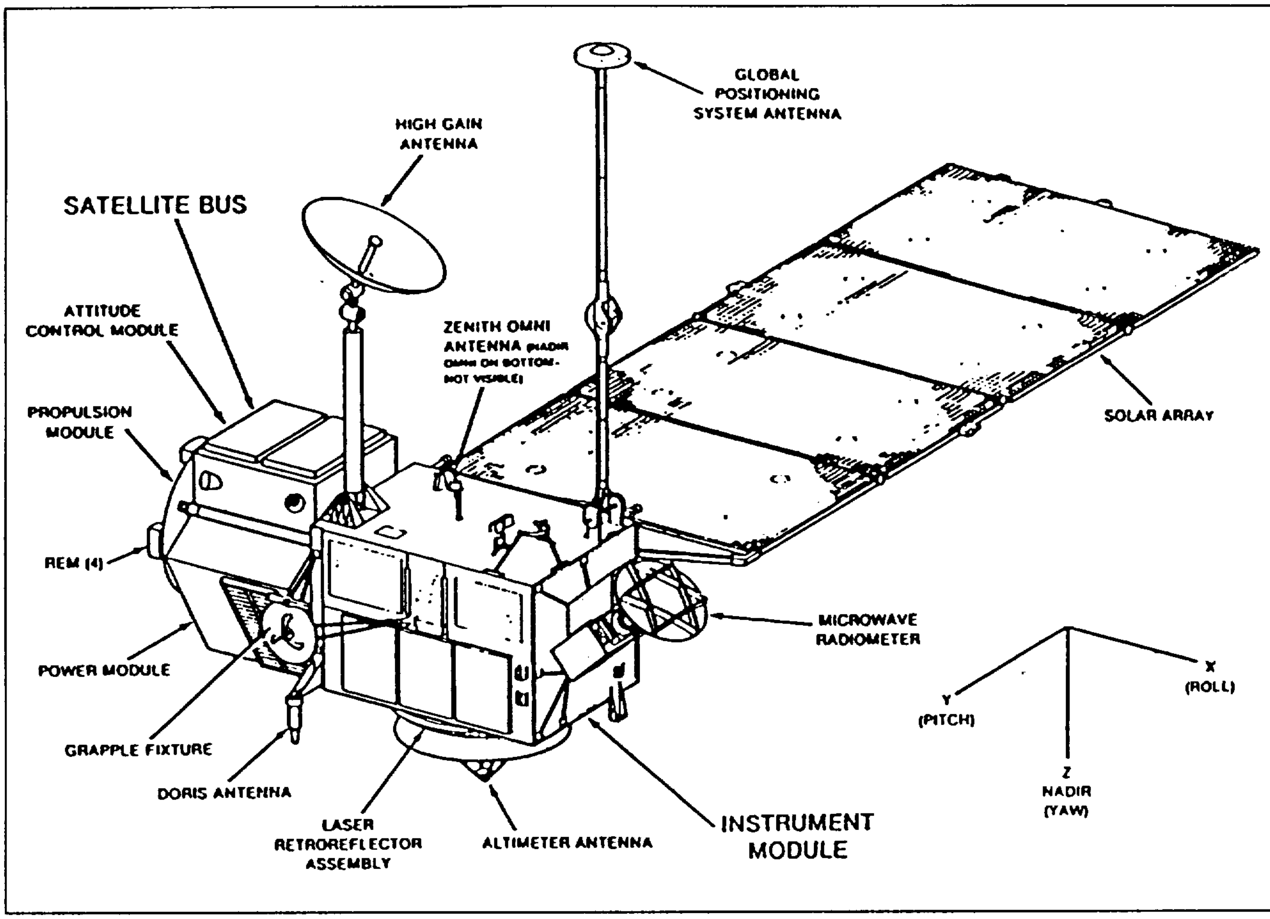


Figure 6.1 Deployed TOPEX satellite (TOPEX/Poseidon Joint Mission, U.S. NASA/Jet Propulsion Lab and France's CNES)

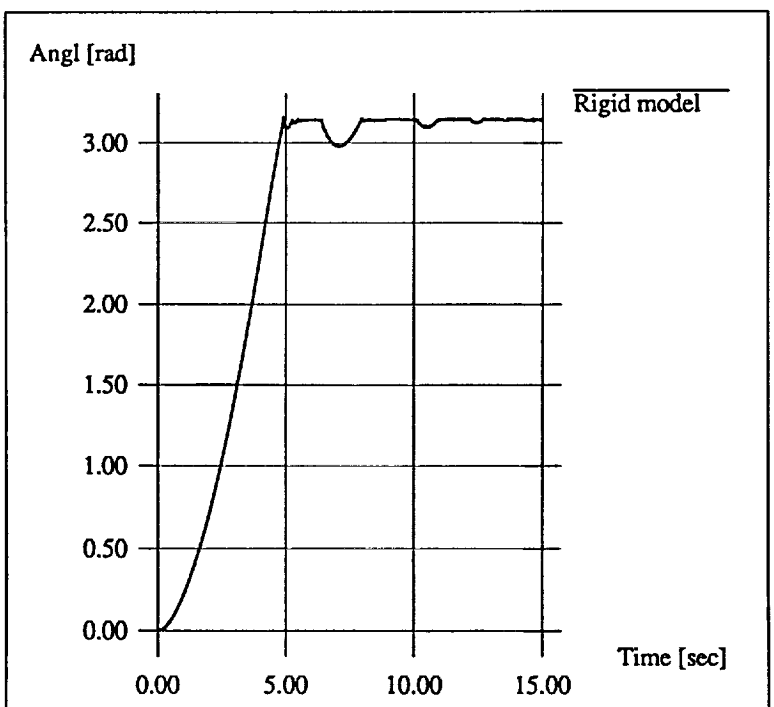


Figure 6.2 Time history of the antenna's mid-range

IDENTIFICATION OF NONLINEAR JOINT MECHANICS FOR DEPLOYABLE STRUCTURES

Steven J. Bullock, Lee D. Peterson

Current research in reconfigurable, adaptive structures is focusing on increasing the mechanism's reliability and predictability. Precise component modeling is one part of enhancing reliability, because good models lead to good confidence bounds in the systems performance. Proper simulation of the deployment process requires component models with the correct inertia, stiffness, damping, and load-transmission properties. Experimental identification of component models is essential because much of the nonlinear joint mechanics depends on heterogenous mechanical properties, such as friction and contact mechanics, the effect of which can only be measured in situ.

This research extends the force-state mapping (FSM) method to derive nonlinear component models for these types of applications. The FSM technique is a subset of a class of nonlinear identification techniques called restoring force methods. The first type of restoring force method was developed by Masri and Caughey. The FSM method was independently developed by Crawley and Aubert at a later date. Since then, restoring force methods have been extended to multiple degree-of-freedom (MDOF) and time-varying systems.

FSM can theoretically accommodate geometric nonlinearities due to the kinematics of large motion, but no experimental work has been reported in this area in the literature. Extending FSM to these types of dynamic systems is the principle contribution of this research.

Restoring force methods assume that a dynamic system obeys Newton's second law of motion for mass that is time-invariant. The system mass can not be a direct function of time, but can vary indirectly over time through dependence on the physical states. The internal, or restoring, force of the system is a general function of the physical states that simply equals the difference between the external forces on the system and the system's inertial force. The measured restoring force can be visualized as a surface over the phase, or state, plane. This plot is called the force-state map of the system.

The true strength of restoring force methods is their ability to fit experimental data to models of physical phenomena. Systems with discontinuities in their stiffness or damping behavior, hysteretic systems, and systems with time-varying stiffness and damping properties have all been experimentally identified. Restoring force methods can also accurately identify Coulomb friction and piecewise linear stiffness behavior. This work extends these results to kinematically nonlinear systems with state-dependent inertia tensors.

The geometric nonlinearities due to the kinematics of large motion manifest themselves in the inertia tensor of the joint. Previous FSM investigations have exploited the fact that the inertia tensor is tangentially constant over a small range of motion. However, it becomes significantly dependent on the motion and configuration of the system when the range of joint rotations or motions become large. Restoring force methods can theoretically model any nonlinearity, as long as the mass matrix is not directly a function of time.

Some of the past year's efforts have been directed toward building the apparatus that allows the testing of joints as they are moved through large angular motions. The pictures show this apparatus (Figure 7.1) and a typical joint (Figure 7.2) from a deployable structure being tested. The joint shown is one of the joints used in a batten-actuated truss testbed used to study reconfigurable structures. Our current research is focused on comparing the results from two different testing protocols. The first protocol fixes the joint in three of the possible deployment configurations. These tests involve exciting the joint about a nominal deployment point, which we call the fixed testing protocol. Under the fixed testing procedure, it is assumed that the joint inertia is piecewise constant. The second protocol tests the joint as it continuously moves through these same deployment configurations, which we call the large-motion testing protocol.

The rest of the past year has been devoted to developing software models and tools for analysis of the experimental data obtained from the FSM testing apparatus. For reconciling the observed FSM behavior, two finite elements models are being developed to model the SDOF joint. An MSC/NASTRAN^R model of the joint at the three nominal deployment positions will be compared to the models obtained from the fixed testing protocol. The second finite element model is a SAMCEF nonlinear, kinematic simulation model of the joint deployment. This model, when at the above deployment positions, will be compared to the MSC/NASTRAN^R model. In addition, it will be compared to the model identified by the large-motion testing protocol. In both finite element models only the joint, pin, and one half of the joint node are actually modeled, using standard handbook values for the material properties of the components. Additional analysis tools have been developed in Pro-MATLAB^R and LabVIEW^R to display the experimental data in various forms, such as contour and surface plots.

Figure 7.1 Force-state mapping test apparatus

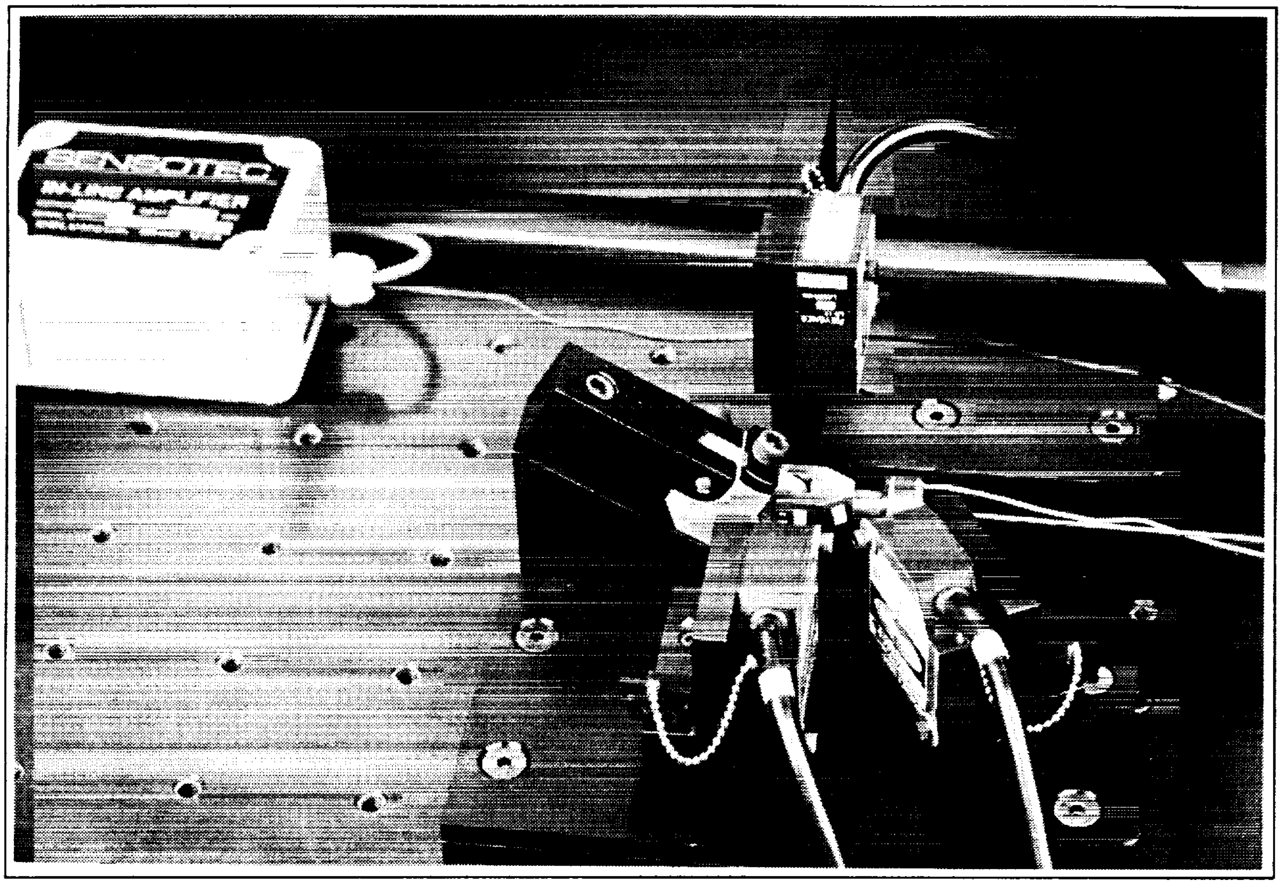


Figure 7.2   Test joint of a deployed structure

MODAL DAMPING MEASUREMENTS OF INFLATABLE SPACE STRUCTURES

M. Roman Hachkowski, Lee D. Peterson, Martin M. Mikulas, Jr.

Inflatable space structures have acquired renewed interest as a possible solution to on-orbit deployment of spacecraft components. Inflatable reflector technology, in particular, is being considered for large-diameter microwave-sensing spacecraft. If successful, this technology will enable the deployment of large-aperture sensing elements for relatively small spacecraft.

A critical structural question, however, is how to manage the stiffness and damping inherent in the inflatable structure on-orbit. This is important not only to resist thermal deformations induced by solar heating, but also because the structural vibrations are considerably slower than for non-inflatable structures. In fact, the attitude control systems of most spacecraft will include the vibration modes of the inflatable reflector within their bandwidth. For this reason, the knowledge of vibration frequency and damping ratios gained from ground-based modal tests imposes an important limitation on the practical use of inflatable structures.

Both the damping mechanisms of the inflatable material and the nonlinear characteristics of the vibration challenge most existing modal test methods. Consequently, the Center for Space Construction has begun a testing program that will focus on developing modal testing and analysis techniques for inflatable space structures. As these tests are apparently the first of their type on inflatable beams, CSC is leading the development of inflatable structures test methodologies.

As part of this development, CSC has begun a cooperative program with L'Garde Inc. of Tustin, CA, in which L'Garde provides prototype inflatable beams to CSC for study. To date, CSC has made preliminary measurements of the damping characteristics of these beams as a function of frequencies. The effects of pressure and thermal loads on the modal test results are also particularly important and are being investigated. We have also developed new techniques for measuring their modal dynamics in a 1-g laboratory.

The original focus of CSC's testing program was to provide independent assessment of analytical models L'Garde is currently using for its upcoming flight experiment, the "In-Step Inflatable Antenna Experiment". As the tests progressed, CSC identified anomalies of the coated fabric beam. As a result of these observations, L'Garde has revised its flight dynamic models with new, updated material characteristics, and has also improved its manufacturing process to increase the accuracy of the inflatable beam.

This and future research results will be used to design and verify future inflatable space structures. This development represents the preliminary definition of a test facility that can be used to test various inflatable structures. Other types of inflatable structures will be tested in the near future.

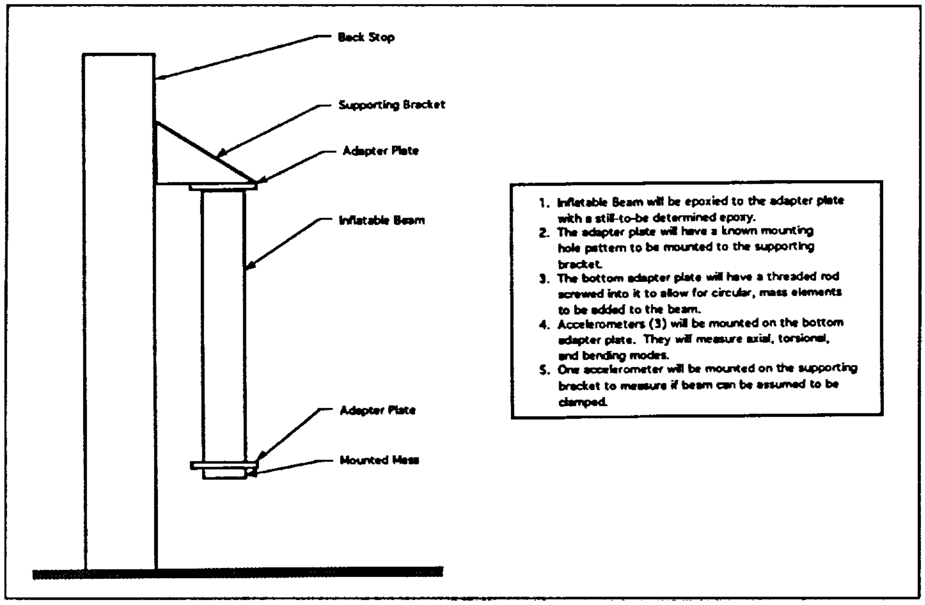


Figure 8.1a Design for inflatable test set-up

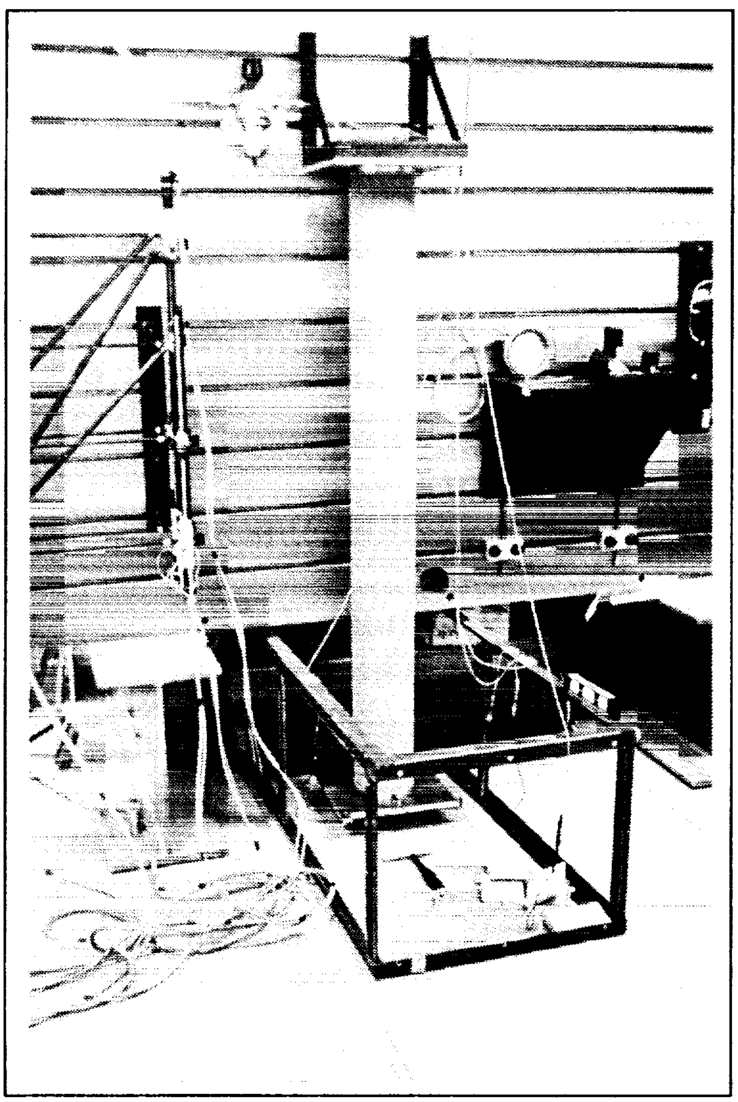


Figure 8.1b Inflatable test set-up

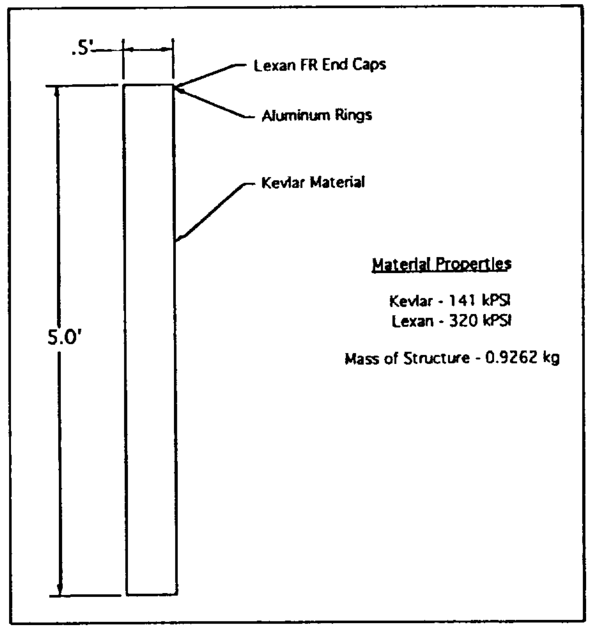


Figure 8.2 Inflatable tube

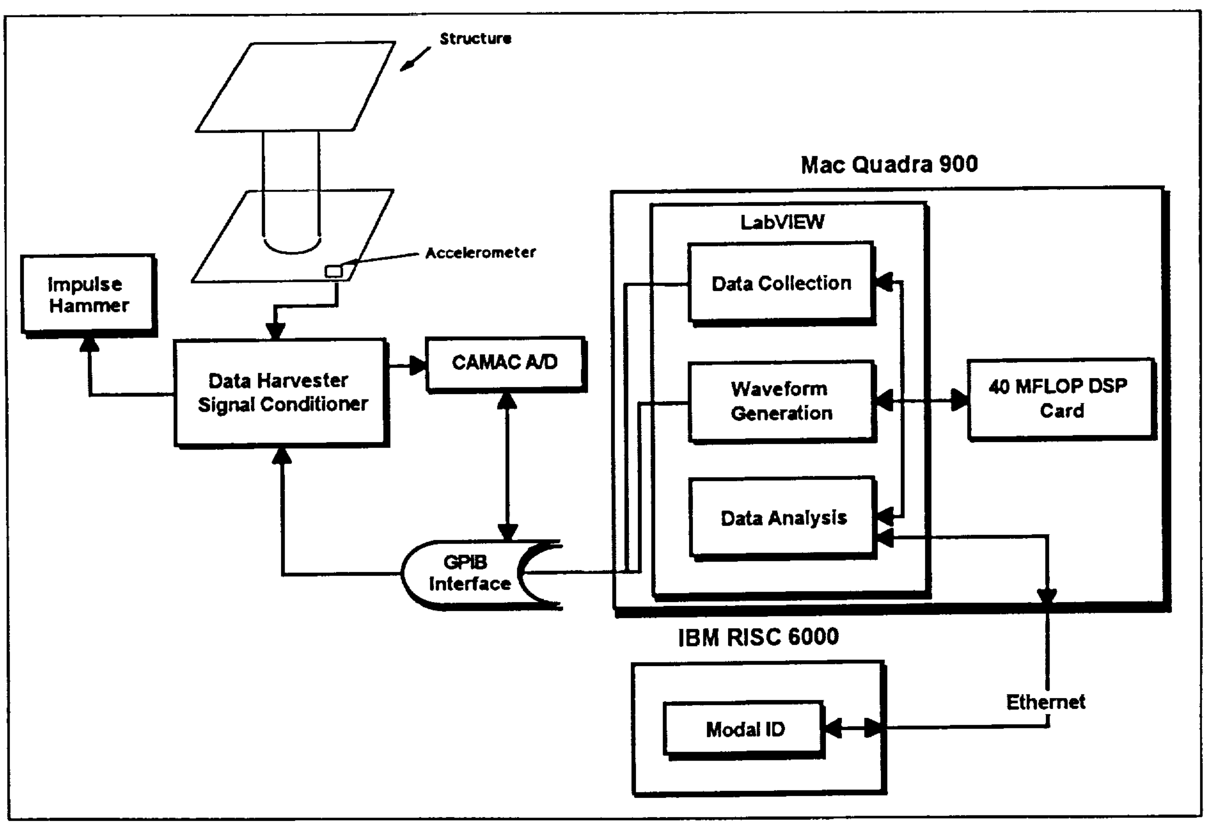


Figure 8.3 Data acquisition system used in testing prototype inflatable beams

A LARGE MOTION ZERO-GRAVITY SUSPENSION SYSTEM FOR SIMULATING ORBITAL CONSTRUCTION AND DEPLOYMENT

Timothy M. Straube, Lee D. Peterson

All orbital missions involve pre-launch ground-based testing of structures. These experiments attempt to model some aspect of micro-gravity to produce an improved prediction of a structure's on-orbit response. An effective simulation requires that the suspension device minimally alter the free-free dynamics of a structure. Many existing suspension devices have the low mass and near-zero stiffness necessary to simulate a free boundary condition—however, most are limited to only a few centimeters of motion. While this range of motion may be appropriate for performing modal analysis, it is unsuitable for measuring deployment dynamics or assembly dynamics, for which the motions required can be on the order of meters.

This research uniquely combines a large-stroke passive off-load device, capable of a one-meter stroke, augmented by electromotive actuated force feedback. This system is therefore capable of performing ground-based simulations of large-motion orbital construction events such as docking, multiple component assembly, and structural deployment. The current focus is on a one-dimensional system which provides freedom of motion in the vertical direction. Test structures of interest will range from 20 to 100 lb with fundamental frequencies as low as 10 Hz. (Our target structure for the design was an eight-bay Warren truss weighing 38.6 lbs with a fundamental frequency of 50 Hz.) For an effective simulation the suspension system mass, stiffness, and friction should be small enough to not influence the free-dynamics of these kinds of structures. Baseline requirements derived from the literature search constrained the net active suspension moving mass to not exceed 5% of the test structure mass, and restricted the fundamental suspension frequency to be a decade below that of the test article. Acceptable friction tolerances vary but indicate 0.01% of the structure weight to 0.1 lbs to be reasonable levels.

The passive subsystem, a zero spring-rate mechanism (ZSRM), capable of large ranges of motion, consists of a torsion spring and a non-circular disk. The test structure is supported by a cable which wraps around the disk after passing across overhead pulleys (Figures 9.1 and 9.2). The disk shape, spring rate, and initial spring deflection are designed so that the spring force, acting on the disk, counterbalance the torque created by the weight of the structure. Vertical structure translations are accompanied by disk rotation and spring deflection. The changing disk radius compensates for the increasing or decreasing spring torque providing continuous test structure off-loading through the rotational range of the disk (Figure 9.3). Ideally, the passive system alone should handle the off-loading duty throughout the entire range. Frictional effects and suspension inertia, however, diminish test article response. Compensation is accomplished via an actively-controlled DC servo motor (Figure 9.4), using force feedback from a load cell reading the tension in the support cable located directly above the test article.

Two tests are being used to determine the effect of residual mass, damping, and stiffness on dynamic characteristics of the test structure. One test will involve imparting a known impulse to a lumped mass test structure, via modal hammer or shaker, and measuring the response. Newton's second law should be obeyed for the stroke of the device. If operating optimally, the load cell should continuously read the weight of the structure. Any deviation can be integrated to provide an error quantification as different control parameters are tried. The second test involves modal testing of a specially-designed beam with a fundamental mode near 10 Hz. Tests in the horizontal plane will not be influenced by the suspension attachment and should represent the true modes of the structure. An identical test in the vertical direction and a comparison of the responses will indicate suspension system influence. Both results will be compared to the response of the structure suspended by a static cable. A finite-element model of the suspended structure will also be used to reconcile the experimental results.

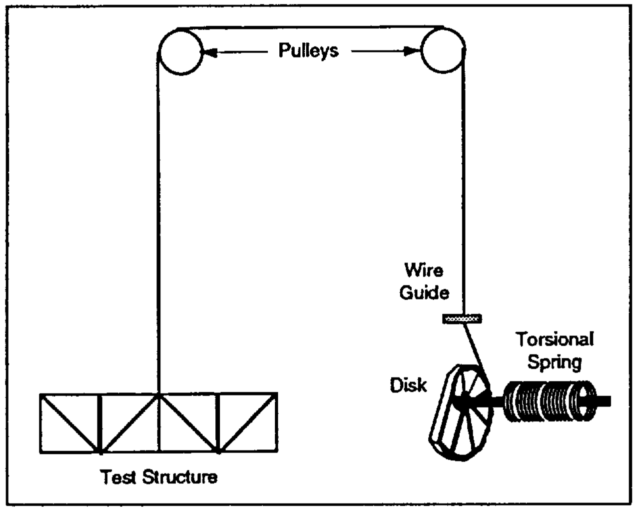


Fig. 9.1 Suspension system test set-up

Fig. 9.2 Suspension system: test structure with mechanism

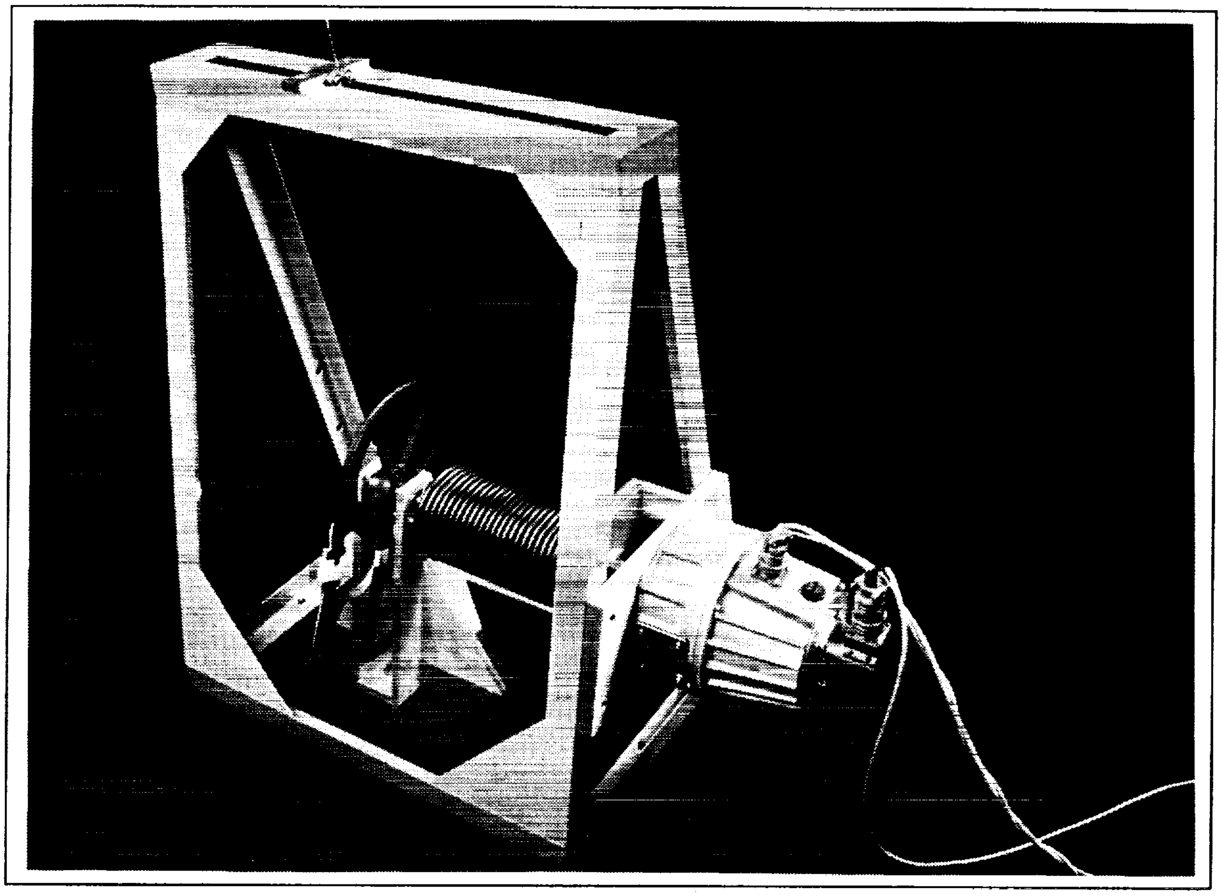


Fig. 9.3 Suspension system: close-up of mechanism

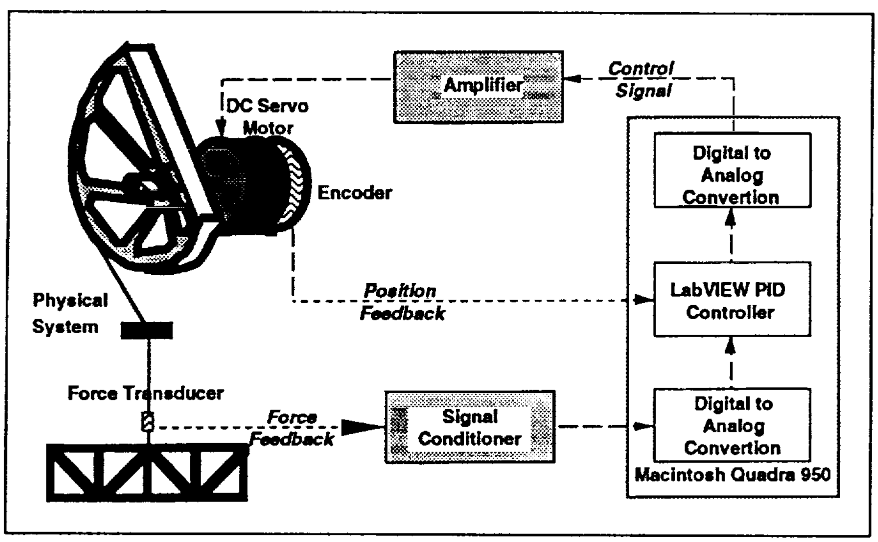


Fig. 9.4 Suspension system: controller signal flow

MONITORING OF SPACE STRUCTURES

Scott W. Doebling, François Hemez, Charbel Farhat, Lee D. Peterson

This research is focused on development of advanced modeling methods for verifying the integrity of structures assembled on-orbit. Health monitoring, also known as damage detection, is the process of evaluating the condition of a structure based on the measurement of some structural characteristics. Since the physical quantities of interest, such as mass and stiffness, can be difficult to measure directly, one must measure related quantities such as modal response characteristics instead. For orbit-constructed spacecraft, these measurements must be made remotely.

There are two main techniques to monitor structural health using modal response information. The first method involves the comparison of the measured response with the response from a finite element model (FEM), which has been investigated through the research of François Hemez and Charbel Farhat. A Sensitivity-Based Element-By-Element (SB-EBE) updating method for improving finite element models using test modal data has been developed. The SB-EBE updating method searches for both the location and potential sources of the detected errors, and does not interfere with the theory behind the finite element model while correcting these errors. An updated model is sought at the element-level by adjusting the model's material and/or geometrical properties. The method has been successfully applied to both model refinement and damage detection cases involving simulated and experimental data.

The second method involves the comparison of the measured modes of the structure in its nominal condition to the measured modes at some later time. The difference in structural response between each pair of measurement degrees of freedom can then be evaluated, with "significant" changes (in a statistical sense) indicating structural damage. This method is computationally attractive and requires no FEM, but it may fail to provide fine resolution of the damage location.

There are three primary difficulties involved in health monitoring. The first is identifying the system parameters in a systematic way; the second is incorporating prior knowledge about the structure into the health monitoring process, and the third is designing the experiment to maximize the information provided by the measured data set from a limited number of measurements.

We have recognized these key problems regarding health monitoring, and we are exploring analytical and experimental techniques to reduce their effect. We are developing the components of an integrated test, parameter estimation and damage detection system which will automate health monitoring of on-orbit space structures. These components include a statistically-based experiment design methodology, which chooses sensor types, excitation signals and measurement and excitation locations to maximize the amount of information provided about critical structural parameters.

Towards these goals, we have achieved the following: We have constructed a health monitoring testbed, consisting of an eight-bay, four-longeron truss. This structure, known as "MUDDE" (Model Update / Damage Detection Experiment) is shown in Figure 10.1 in its modal test configuration. We have added concentrated masses in an asymmetric manner around the truss, which have a total mass equal to that of the truss. These distributed masses induce extremely localized modal behavior. For example, the first several modes of this structure consist of the larger masses rotating back and forth, concentrating most of the strain energy in the members adjacent to these masses, as shown in Figure 10.2. Since the rest of the members store little energy in these modes, altering their stiffnesses does not significantly affect the response of the structure. Thus, damage in these members is difficult to locate. In a structure with traditional "beam-like" modes, however, the strain energy is well-distributed and many more of the members store energy, so changes in their properties do affect the overall response of the structure. In that type of structure, the damage is more easily located.

A comparison of two typical frequency response functions for the MUDDE structure is shown in Figure 10.3. The solid line represents the response of the nominal structure, and the dashed line represents the response for the same input/output pair after the removal of only *one* longeron. The large shifts in modal frequencies are characteristic of damage in this type of complex structure, as are large changes in the mode shapes. In fact, the response of this structure changes so much after the damage is applied, that it is difficult to perceive the resulting response as a perturbation of the original. It appears to be an entirely different structure.

We have conducted two damage detection experiments on this structure, and have used the data to successfully locate the damage using the sensitivity-based element-by-element technique. Using the algorithm shown in Figure 10.4, we studied the effects of modal data set selection on the success of the FEM update. Since, although the structure contains hundreds of modes in the bandwidth of interest, only a few modes may be used in the model update (due to the aforementioned computational intensity), the analyst must decide which modes are the best ones to keep. Traditionally, the lowest N modes are kept, where N is determined by computational limits. We have demonstrated that it is better to choose the N modes containing the most strain energy, since they will have the highest sensitivity to structural damage. We are planning a third experiment soon to evaluate our technique for non-FEM based health monitoring. This research follows the work of Ken Alvin, Lee Peterson, and K.C. Park, who have developed a systematic method for extracting physically meaningful structural parameters from measured modal data. We are also developing statistical methodologies to determine optimal experimental parameters for detecting and locating the damage in complex distributed structures by maximizing the sensitivity of the measurements to parameters that are important to damage location.

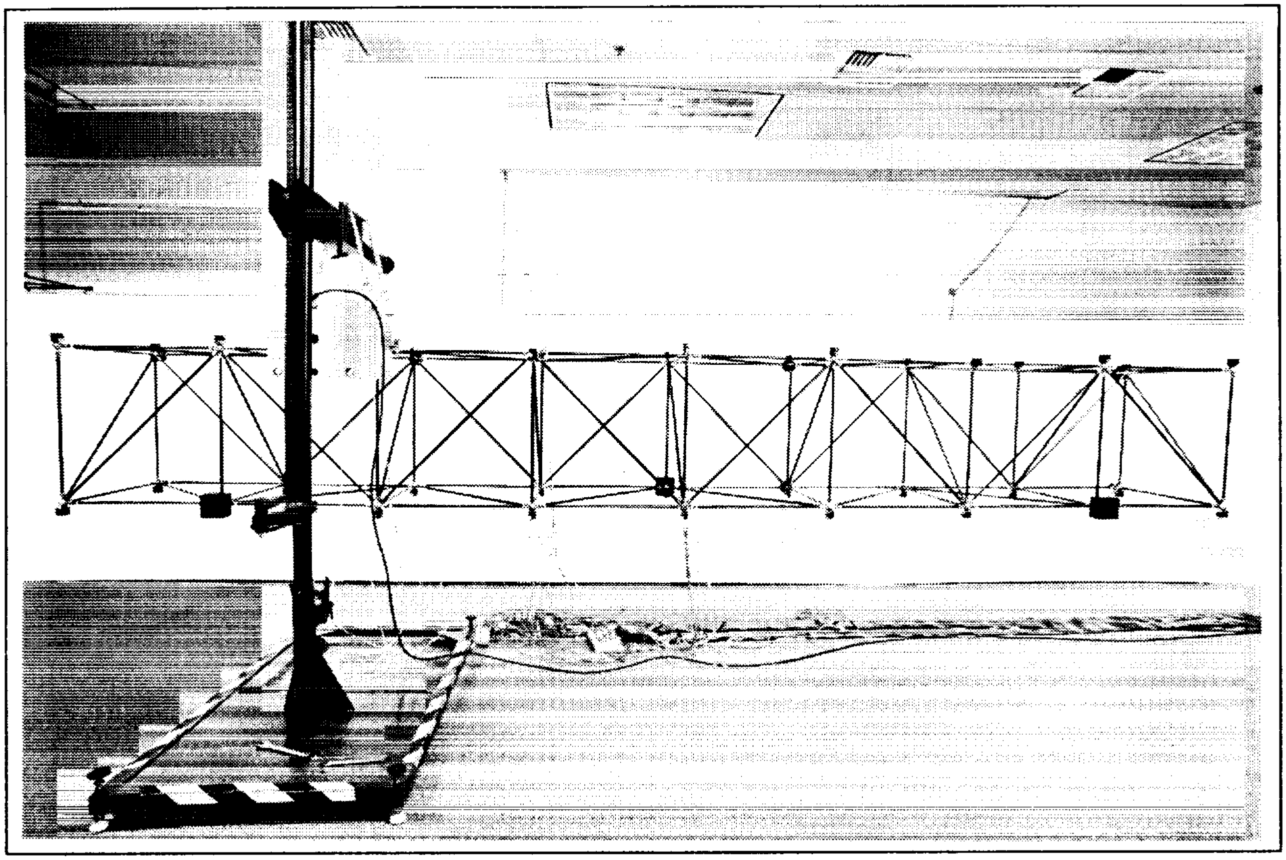


Fig 10.1 The "MUDDE" structure in its modal test configuration

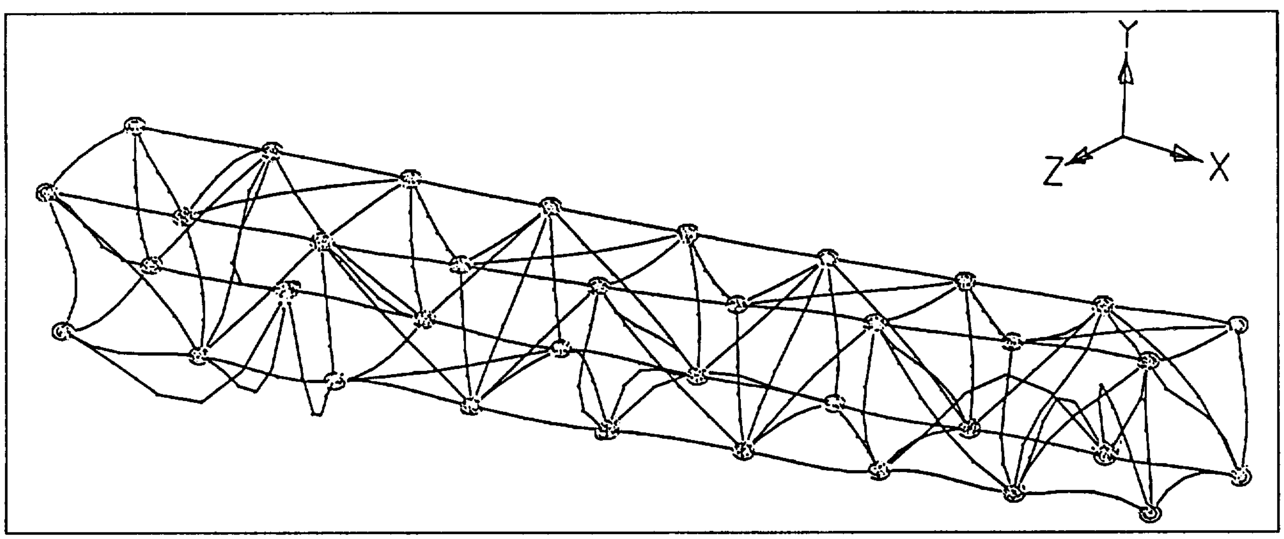


Fig 10.2 The first mode of MUDDE as predicted by FEM

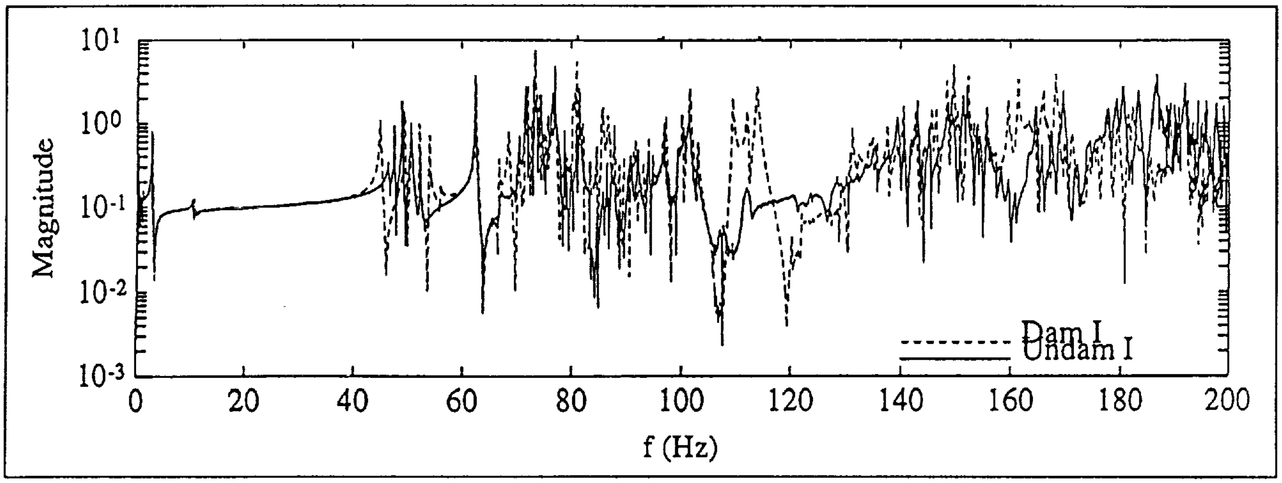


Fig 10.3 Typical frequency response of MUDDE for undamaged and damaged conditions

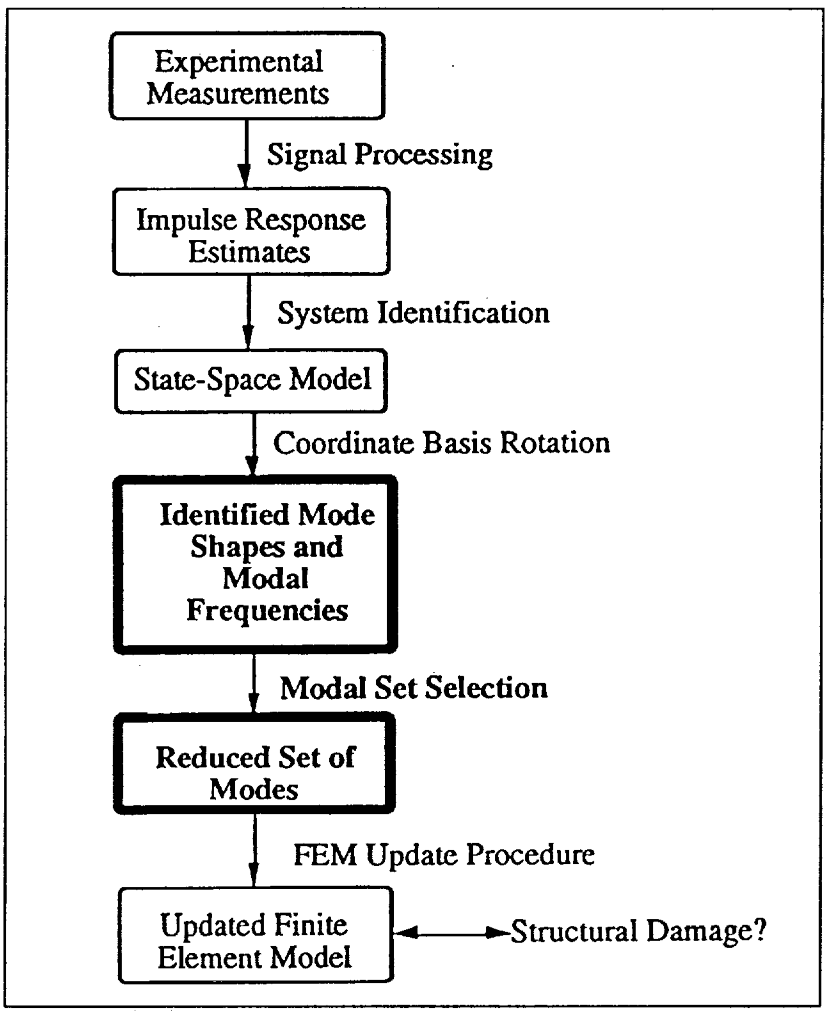


Fig 10.3 The damage-detection algorithm used in this study

ON-ORBIT REPAIR: WELDED FLUID SYSTEMS

Steven Jolly, Clyde S. Jones III (NASA-MSFC)

Welding in space will be an important process for the permanent repair of both low and high pressure fluid-line assemblies used on large spacecraft. Space Station fluid system designs are typical, and they provide a variety of tubing materials, sizes, pressures, and working fluids. Realistic repair scenarios must also include ancillary systems that result in geometric and system constraints to the repair process.

Damage to on-board fluid systems will occur as a product of faulty or fatigued joints, micro-meteoroid impacts, collision with other objects, and overpressure strain or burst. Because welds provide better reliability than mechanical joints, from the perspective of strength (stiffness) and leakage, they were selected for the Space Station Freedom (SSF) fluid line fabrication.

Incorporating experience with terrestrial automatic pipe-welding tools, with that of both the U.S. and former Soviet Space programs in space welding, CSC and NASA-MSFC have analyzed hypothetical repair scenarios for SSF. In this work we derived weld joint design criteria, conceived a new weld joint for in-space repair which meets system-derived criteria, and performed a stress analysis.

The subject of the research was a representative SSF design in which tube assemblies (TAs) run both internally and externally with respect to the habitats. These TAs, in up to 50-ft. continuous lengths, are constructed mostly of AISI 316L stainless steel tubing, but also include some Inconel 625 nickel-iron and Monel 400 nickel-copper alloy tubing. The outer diameters of the tubes range from 0.25-1.25 inches, and the wall thicknesses from 0.028-.095 inches. The system operational pressures range from 377 psi (for the thermal control system) to 3400 psi (for the high pressure oxygen and nitrogen supply lines in the life support system).

Although the current NASA procedure may be to temporarily patch the lines by clamping metal c-sections over the defect, and then perform high pressure injection of a sealing compound, it is clear that permanent repair of the line(s) is necessary. This permanent repair could consist of replacing the entire TA in the segment, or the segment itself—both alternatives being extremely expensive and risky. The former would likely require extensive EVA to release TA clamps, posing great risk to other engineering subsystems, and the latter would require major de-servicing of the Station.

Figure 11.1 illustrates the drivers for the weld-joint design. These considerations became the design criteria for the study. The criteria are:

1. The weld joint design for in-space repair applications must provide much greater compliance (with respect to cutting the TA and the replacement) than the maximum allowable gaps of the standard butt-weld (.008 inches), perhaps on the order of .5 inches.

2. This compliance must be gained without surrendering weld quality and post-weld structural performance, so that a positive margin exists within the standard SSF factor of safety.

3. As much as possible, the weld joint needs to be self-aligning and self-latching.

4. The hardware should be designed and fabricated with the astronaut's s glove in mind—as large as is feasible, and easy to handle.

5. The repair procedure and associated hardware design should minimize the required orbital support equipment.

6. If possible, the weld joint and weld procedure should minimize contact of the weld pool with the inside diameter of the tube assembly, *assuming* that the fluid residuals are degrading to the weld process, or that subsequent cleaning of the TA interior is required in order to return it to service.

Considering these design criteria, the most logical, generalized weld joint design to consider for in-space TA repair applications appears to be one like that shown in Figure 11.2. The primary stresses in this concept are a result of internal pressure on a thin-walled vessel. Commonly called hoop and axial stress, they can be predicted with the thin shell theory of classical mechanics. For values below the elastic limit, Figure 11.3 shows a simple model for computer evaluation and allows "quick-look" design analysis.

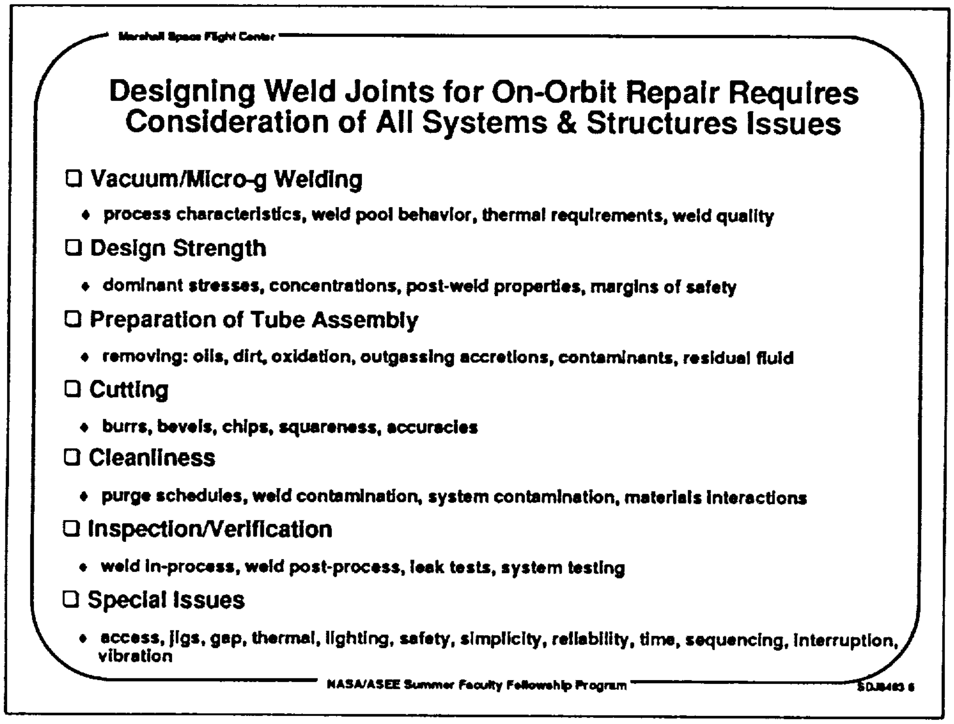


Fig. 11.1 Issues for design of weld joints for in-space repair

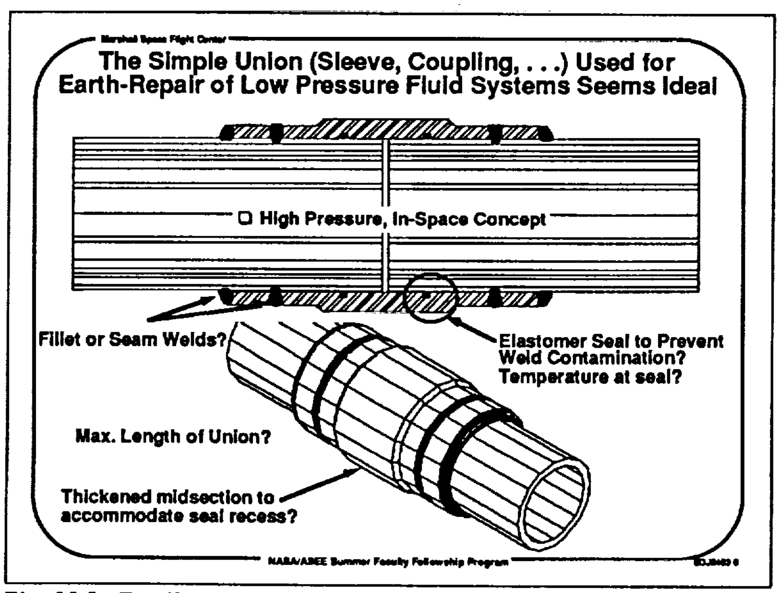


Fig. 11.2 Family of concepts using either fillets or seams (with or without seals)

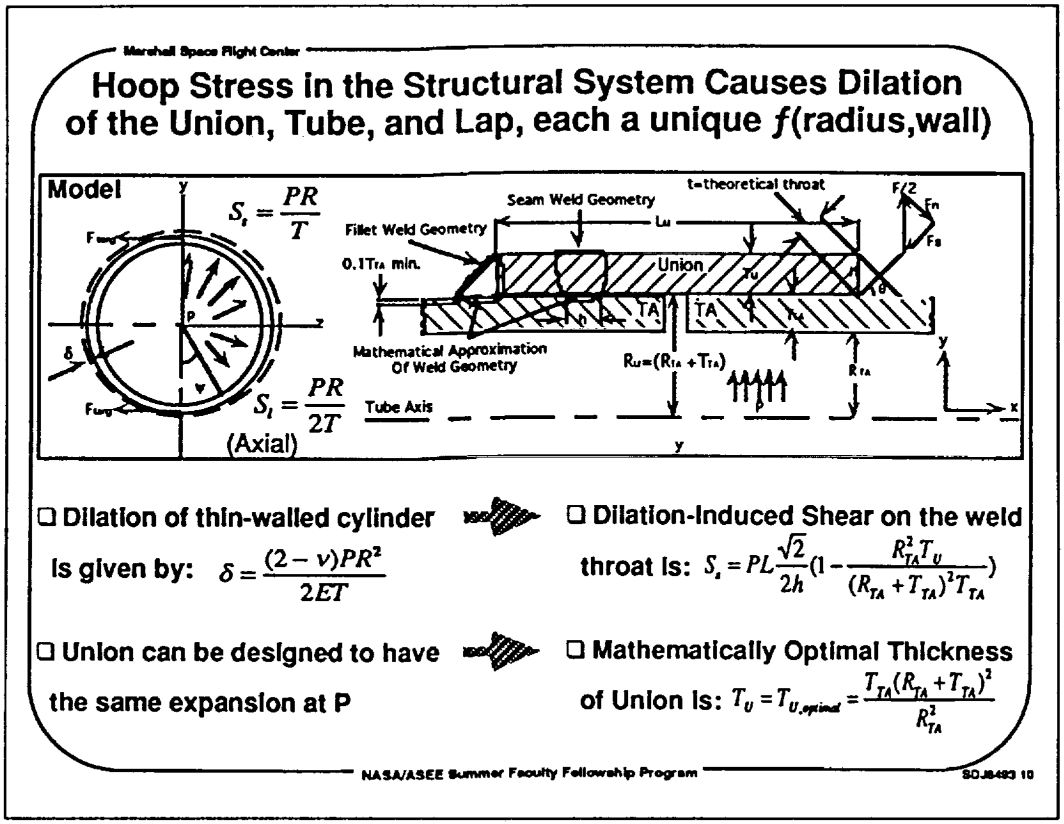


Fig. 11.3 Stress analysis model of weld-union concept

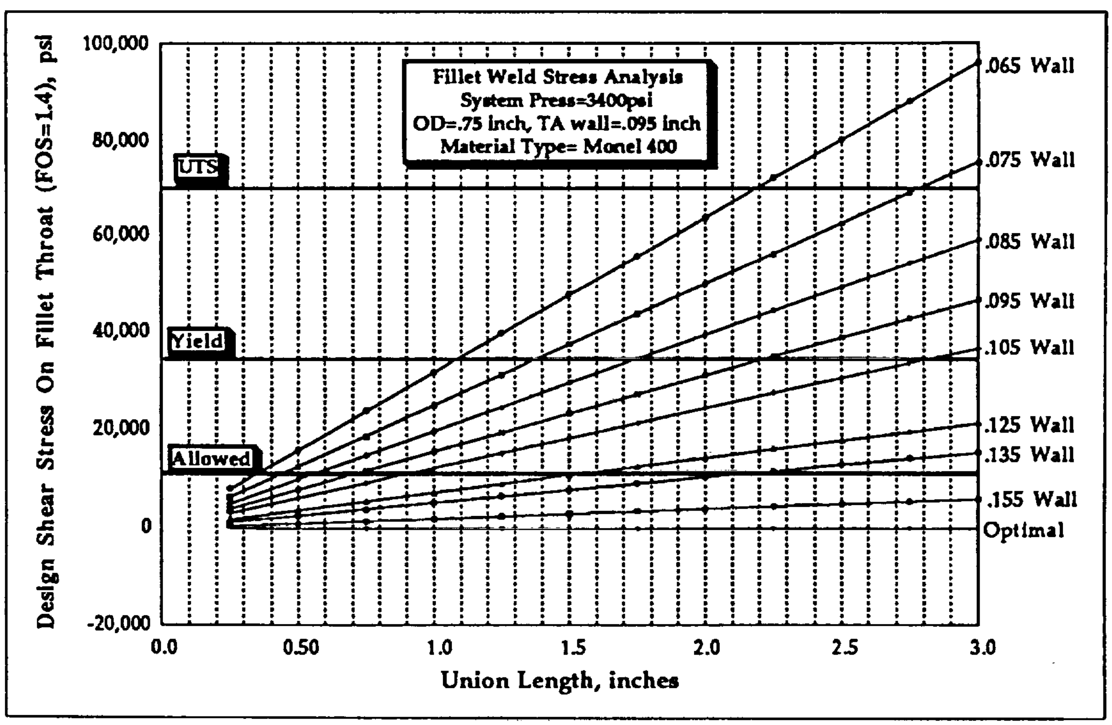


Fig. 11.4 Analysis yields positive margins for near-optimal union thicknesses

CONTROL OF ADAPTIVE STRUCTURES: DESIGN THROUGH SIMULATION

Scott Alexander, K.C. Park

This project investigates the design of flexible multibody control algorithms using dynamic simulation.

The ability of living organisms to reorient themselves in the absence of external reaction forces has long been studied. Investigations into the motion of spring board divers, astronauts, and the rotational maneuvers of a falling cat have concluded that global reorientation of a multibody system is possible using purely internal torques. This concept has been used by investigators to derive a control algorithm for the planar reorientation of a three-link rigid chain using only internal joint torques. In this problem, a simulated satellite with a deployable antenna is required to deploy the antenna and achieve a specified rotational orientation. This is accomplished using feedback linearized control and a feed-forward control history.

The goal of this investigation is to extend these concepts to the control of flexible multibody systems, like the reconfigurable truss shown in the figure. Control design for flexible multibody systems will play a large role in space systems development. Remote manipulator arms, deployable antennae, and deployable trusses are only a few possible applications. It designs a control force history based on dynamic simulations of the system. During the simulation, constraints on the system will be added to force the system into different configurations. The resulting constraint forces are then considered the necessary control forces. The final control will therefore take into account the dynamical considerations implied by the constraints, as well as the original maneuvering objectives. Judicious choice of the constraints will thus improve the overall system performance.

This project consists of three phases. The first task, which has been completed, implemented general nonlinear finite element dynamics analysis software capable of handling the imposed constraints. We wrote a nonlinear dynamics analysis code, and combined it with an optimization software package. The optimization is required to handle any nonholonomic inequality constraints.

The second task is to develop the particular constraint conditions necessary to create the desired behavior, and analyze the time history of the constrained system. The second phase is underway, with analysis being done to derive a constraint capable of controlling the three link rigid chain mentioned above. Once these constraints have been found, they will be generalized to handle a broader class of problems.

The third task will be to utilize this information in the design of control algorithms for general nonlinear flexible multibody systems.

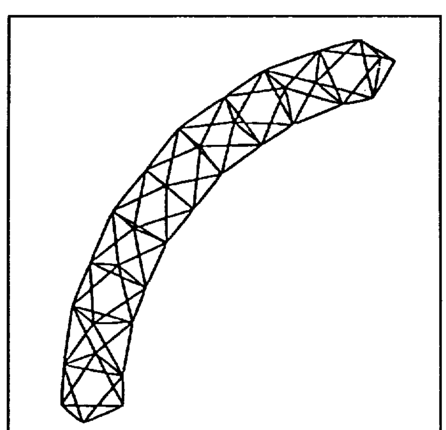


Fig. 12.1 Reconfigurable truss beam

INTERACTION CONTROL FOR ON-ORBIT ASSEMBLY AND JOINING

Dale A. Lawrence, Philip G. Good, Jay St. Pierre

Spacecraft which are pre-assembled on the ground are limited in size by launch vehicle capabilities. Spacecraft many times larger and more massive can be constructed by assembling smaller spacecraft components on-orbit. A variety of assembly scenarios have been studied, using a variety of assembly "tools." At the simplest engineering level, incremental assembly of the smallest, most elemental components (e.g. individual truss struts) via direct human labor (EVA astronauts) has been demonstrated, but the projected EVA time and associated mission costs and personnel risks are significant. It may be more efficient to pre-assemble and pre-integrate the largest possible spacecraft sub-systems on the ground, then assemble a relatively small number of these large components on orbit. The size and mass of these components are beyond the capabilities of one (and quite possibly of several) EVA astronauts. Therefore, specialized assembly aids and tools are required. The remote manipulator system (RMS) could be considered such an assembly aid, as well as other planned systems such as the special-purpose dextrous manipulator (SPDM).

This project has focused initially on the control of such assembly aids to trade off the conflicting objectives of (a) soft initial contact to minimize shock versus (b) stiff positioning to effect permanent structural joining, utility connection. Its main contribution thus far is the development of a decentralized control method which utilizes sensor information local to the assembly tool. In this way, costly communication of real-time control information between assembly components can be avoided, and the control law in the assembly tool can be greatly simplified. The technical basis for this work is a specialization of general residual mode filter (RMF) and disturbance accommodating control (DAC) ideas to the decentralized assembly control problem. The resulting controllers consist of two independently-designed layers: (1) a nominal interaction control which establishes the fundamental trade-off between low component interaction forces and high relative-position accuracy, and (2) an auxiliary interaction controller which stabilizes any elastic vibration modes which are adversely affected by the nominal interaction controller. These modes are small in number, existing in the "transition region" between those low-frequency dynamic modes included in the nominal controller design, and the numerous high-frequency modes which are not affected due to limited nominal controller bandwidth. As a result of the relative low dynamic complexity of this transition region, a relatively simple auxiliary interaction controller is possible.

The Center for Space Construction has constructed a testbed for these initial developments in control of assembly tools. It consists of an air-bearing table, a multiprocessor real-time digital control system, and various sensors, actuators, and experimental assembly components. The first comprehensive assembly experiment is nearing completion, in which component interaction during contact and assembly along a single degree-of-freedom are carefully studied and compared to simulation data. The objective of this experiment is to assess the practicality and robustness of the theoretical methods previously developed for local interaction control. Results of this experiment will provide valuable data and insights to guide future research in orbital assembly techniques and devices.

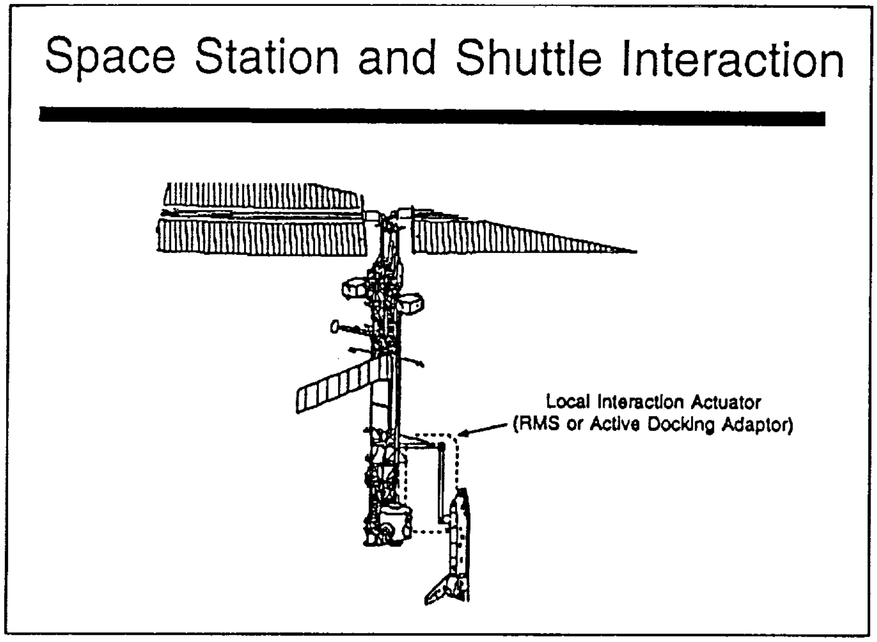


Fig. 13.1 *Example application of the local interaction control method in space station assembly, using RMS as the assembly "tool."*

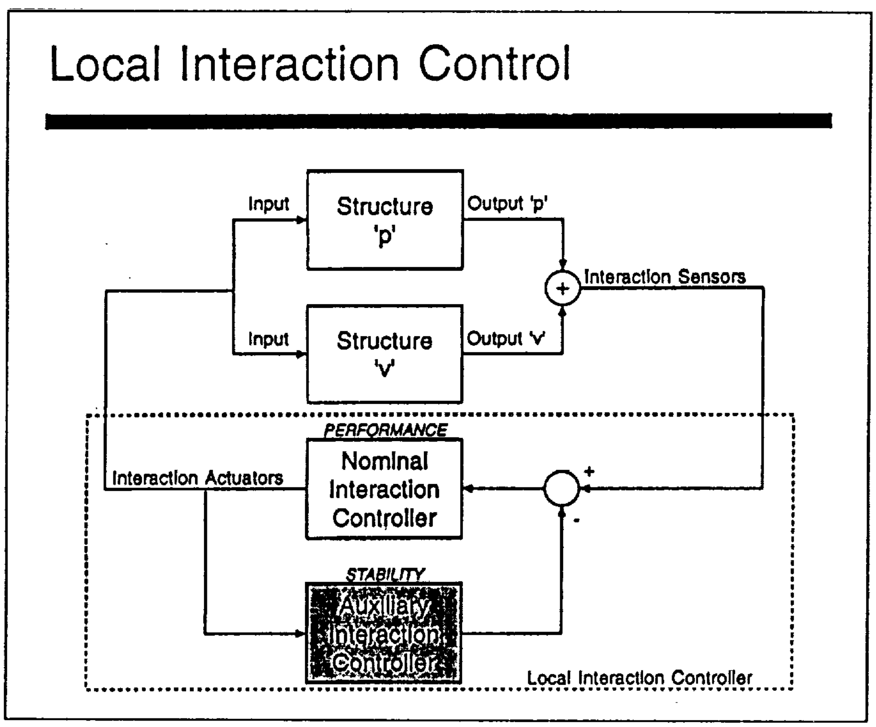


Fig. 13.2 *Block diagram description of two components (structure "p" and structure"v") brought into contact by the nominal interaction controller, with compensation for dynamic instability provided by auxiliary interaction control.*

Simulation Response

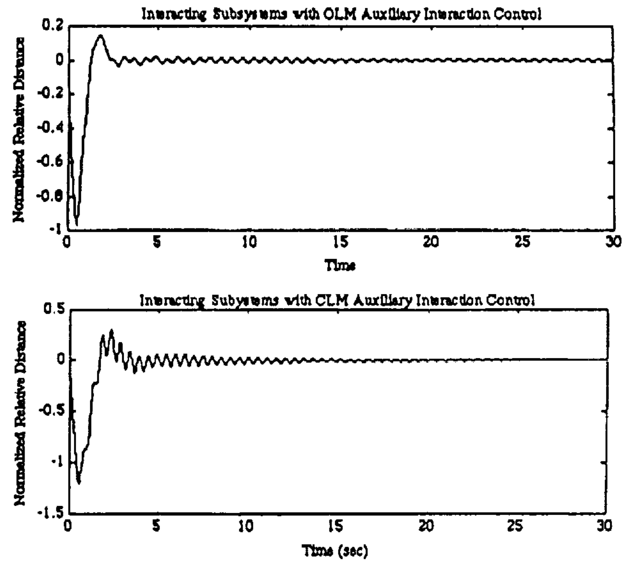


Fig. 13.3 Simulation results showing a slow response determined by the nominal interaction controller trading off contact force and relative component motion. Also visible is the characteristic small, slowly-decaying vibration resulting from the stabilization of a dynamic interaction instability.

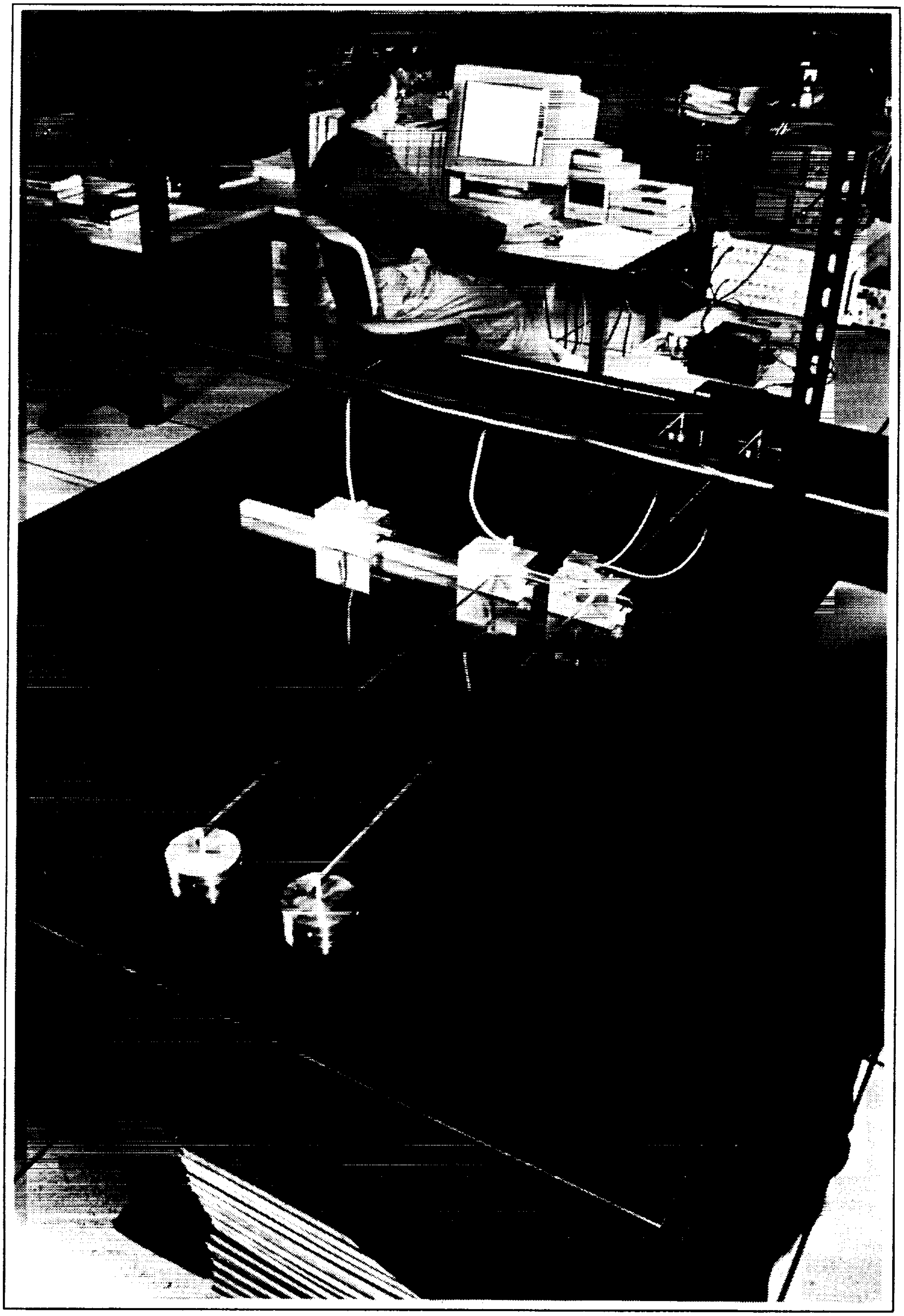


Fig. 13.4 The testbed used to evaluate the local interaction control method. This is a simplified representation of the space station assembly scenario shown in Figure 13.1, designed to capture only the essential dynamic effects in the important "transition region" between modeled dynamics and gain-stabilized dynamics.

STABLE ASSEMBLY OF ACTIVE SUBSYSTEMS USING PERTURBATION METHODS

Lawrence "Robbie" Robertson III, Mark J. Balas

This CSC project studies the use of perturbation methods to achieve stable assembly of active subsystems. The large size of many proposed space-based vehicles necessitates on-orbit assembly. This process will undoubtedly involve the assembly of controlled substructures to form the finished vehicle. Unfortunately, very little is known about how to control such structures before, during and after the berthing process. Such constraints as minimal or nonexistent communication between controllers, the need for fail-safe modes, and performance requirements for the completed structure further complicate the design. Presently, control design strategies such as linear quadratic regulators, *h*-infinity methods and reduced-order model/residual mode filter have demonstrated their ability in handling fully-assembled structures, but have not proven their worth or been tested in an operations environment.

To model the assembly process of two substructures with no interaction controllers, we introduced a perturbation parameter between the two substructure stiffness equations (Figure 14.1). By making an assumption that the control system is designed for stability when the substructures are disconnected (Figure 14.2a), we analyzed the stability of the connected system by varying the perturbation parameter. The resulting solution, found by using perturbation techniques and norms, was a range of the perturbation parameters over which the system is stable given some controller design (Figure 14.2b). Since the problem is formulated without any assumptions about the controller design, this gives a method for analyzing any control design and does not restrict solutions to the trivial "no controller" or low gain solutions that classical decentralized control usually gives, although the solution is still characterized by conservative bounds (Figure 14.2c).

This method of analysis can be used as an enabling technology in other decentralized applications such as power systems and market models.

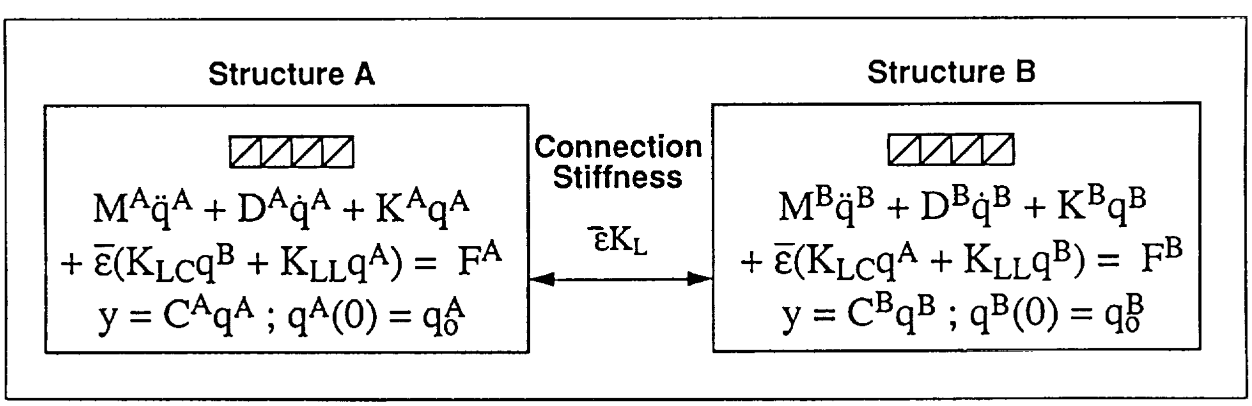


Fig. 14.1 A perturbation approach to problem formulation

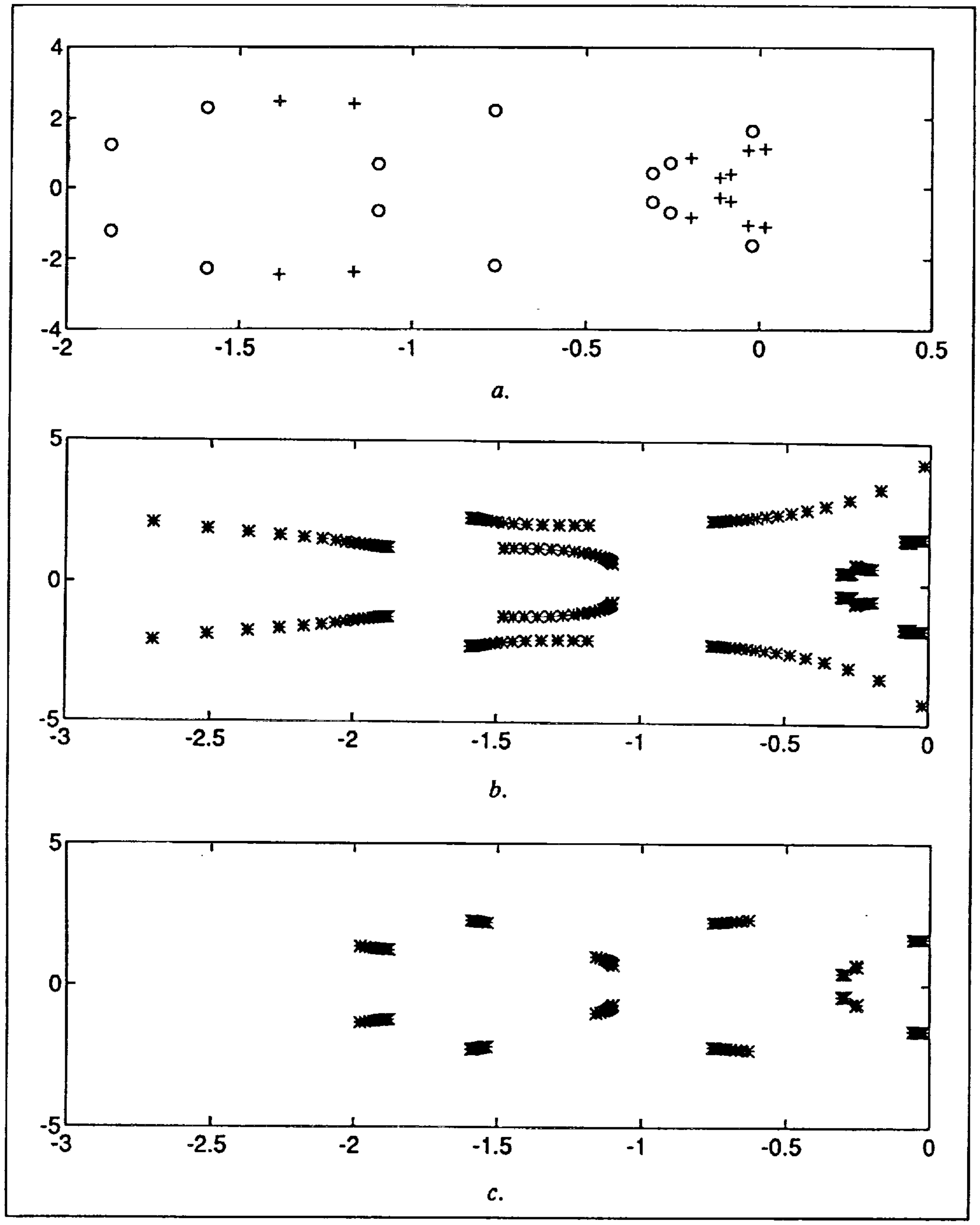


Fig. 14.2 Closed-loop poles of an example: a) connected and unconnected, b) by varying epsilon from zero to one-half, and c) by varying epsilon from zero to one. Example used consists of two four-mass, three-spring substructures.

CONFIGURATION-SHAPE-SIZE OPTIMIZATION OF SPACE STRUCTURES

Carlos Felippa, David Vandenbelt

The objective of this project is the development of computer-based procedures for configuration-shape-size optimization (CSSO) of space structures under construction and/or operational constraints. These constraints may include packaging, deployment and reconfiguration of orbiting structures, and fabrication, transportation and shielding of planetary structures.

The project consists of three phases. In the first project phase the material-removal CSSO procedure introduced by Kikuchi and Bendsøe (abbreviated as KB in the following text) is further developed with two goals in mind: (1) gaining understanding of finite element homogenization methods, and (2) developing and testing constrained optimization algorithms that efficiently carry along thousands of design variables.

In the KB procedure an optimal structure is "carved out" of a design domain initially filled with finite elements (as an example, see Fig. 15.1) by allowing a perforation (hole) to develop and grow within an element. The orientation parameters of the hole for each element become the design variables of the optimization process. Therefore, each two-dimensional element has 3 design variables (see Fig. 15.2). A problem of 100 elements contains 300 design variables.

These design variables are optimized with a minimum strain energy function subject to a given minimum volume constraint. Hence a constrained optimization algorithm is used to determine the optimal structure, however, this algorithm must be efficient for a very large number of design variables. Of all the constrained optimization algorithms available, we have so far found the augmented Lagrangian method to be the best for a very large number of design variables, but testing is still in progress.

Although a large number of design variables optimization solution is still being tested, we have solved problems of small numbers (see Fig. 15.3, which corresponds with the design domain given in Fig. 15.1). These preliminary experiments indicate that the CSSO-KB elements may not be useful for orbiting space structures applications. For most orbiting space structures the optimal design is a truss structure. With the CSSO-KB elements truss struts would be produced by a very small volume. This causes numerical difficulties in the optimization process. Therefore, a new element must be created.

The second project phase involves the development of this new element (shown in Fig. 15.4). This element finds the optimal orientation of truss struts in each element, given a design domain. The area of each strut is related to the given volume constraint. The strain energy that is minimized depends on the orientation and area of the truss struts in each element through the calculation of its stiffness. Therefore, the optimization process is the same as one used for the CSSO-KB elements, but the calculation of the elemental stiffness changes.

In calculating the elemental stiffness the equations for the stiffness of a strut are transformed to correlate with each node of the quadrilateral element. The strut stiffness and the transformations depend on the design variables that describe the orientation of the strut. To calculate the strut stiffness and transformations, the design variables are used to define the x and y coordinates of the end nodes of the strut (nodes 5 and 6 in Fig. 15.4). These equations must be continuous for the optimization process to work, therefore, continuous functions for the intersection of the strut and the quadrilateral must be derived. Presently the transformations have been completed, but the continuous functions for the end node coordinates are still under development.

The third project phase involves analysis of these optimal structures for construction and operational constraints with emphasis on packaging and deployment. This phase is not being considered at this time. Once the results of the first and second phases are complete, development of the third phase will begin.

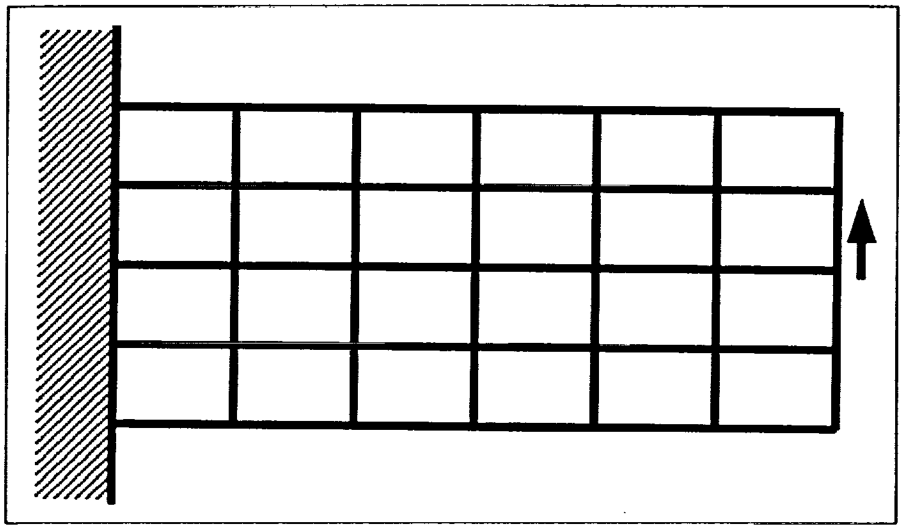


Fig. 15.1 A design domain subdivided into rectangular finite elements

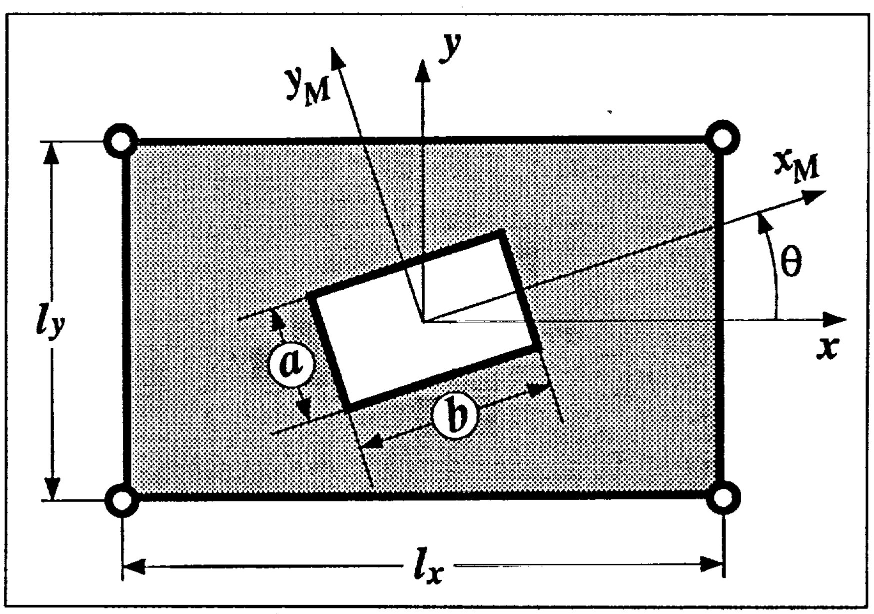


Fig. 15.2 A perforated rectangular element

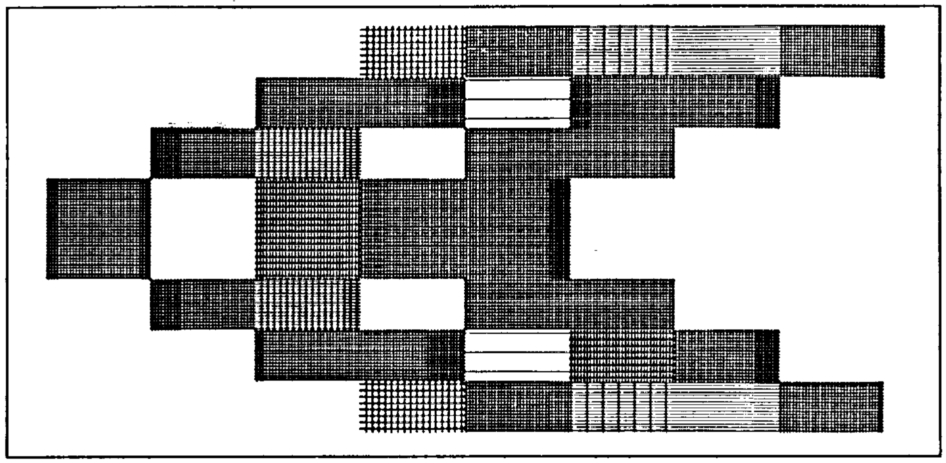


Fig. 15.3 Results from CSSO-KB elements used in Kikuchi-Suzuki benchmark problem (Fig. 15.1) with 8x8 DDM mesh and 50% volume constraint

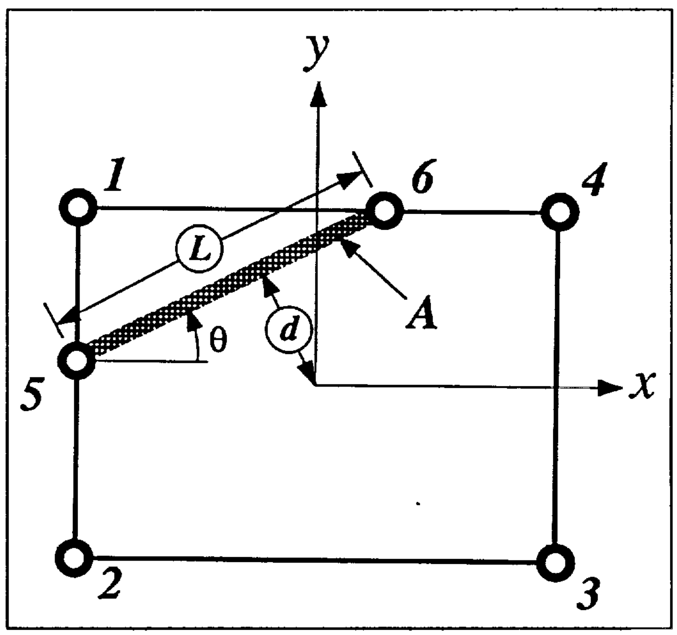


Fig. 15.4 Two-dimensional element to optimize a truss structure

SPACECRAFT DESIGN AND CONSTRUCTION: ARTIFICIAL INTELLIGENCE FOR CAD-INTEGRATED PROCESS PLANNING

George W. Morgenthaler, Kendall M. Nii, Steven Jolly

The goal of this research is to create models which allow conceptual design engineers to analyze a design for constructability. The rationale for the research is based on the common concurrent engineering theme, that when these analyses can be performed early in the design process, the resulting product is of higher quality and lower cost.

Versions 2.0 and 3.0 of CSC's DYCAM (Dynamic Construction Assembly Module) showed that it was possible to use CAD-integrated artificial intelligence (AI) techniques to generate a set of feasible manifests for use in constructing a nuclear thermal Mars transfer vehicle while on orbit. This was CSC's initial foray into the realm of semi-autonomous process planning. DYCAM 2.0 was successful in manifesting the chosen nuclear thermal Mars transfer vehicle within the mass and volume constraints of a generic heavy lift launch vehicle.

The experimental methods employed in the DYCAM research have centered around the AI blackboard metaphor which we render "domain-dependent" by creating domain expert knowledge sources. The blackboard metaphor is an organizational analogy to a meeting of human experts in a "brainstorming" session around a physical blackboard. The "experts" or knowledge sources can interact with the problem on the blackboard and are controlled by a "moderator" or controller (see Figure 16.1).

EXTREME (the Experimental Tool for Research in Manufacturing Engineering) is a new model designed for both terrestrial and orbital manufacturing/construction operations. EXTREME centers around the more difficult problem of process planning for manufacturing and construction of spacecraft and aerospace hardware.

EXTREME will use an AI blackboard development environment called BB1, which we acquired from Stanford's Knowledge Systems Laboratory (Departments of Medical and Computer Science). Currently, the solid modeler being used is the AutoCAD™ 3-dimensional solid modeler. By linking the CAD modeler to the blackboard, EXTREME can create an environment which will be able to analyze CAD drawings and develop feasible machining sequences. Eventually, CSC will develop the next-assembly blackboard (Nabb). EXTREME is the first step toward that goal (See Figure 16.2).

The first step in creating EXTREME is to be able to examine a given CAD drawing and determine certain characteristics of the part to be constructed in the drawing. This information includes basic shape of the part, location and size of holes, materials used, dimensions, and tolerances.

Currently we are working on a system of exporting the necessary information from an AutoCAD™ drawing, and importing it into the blackboard for processing. The next stage is to create a simple expert system to analyze the information from the drawing. If it can be shown that it is possible to make an intelligent analysis of the drawing, then we will have accomplished a very large first step towards developing the NAbb system.

We plan to create a proof-of-concept model for the entire NAbb shown in Figure 16.2. This model will be capable of producing "non-serial" process plans for assembly of a spacecraft, given a "conceptual design". "Conceptual design" is defined as a geometric or solid-body model combined with the basic capabilities of each subassembly.

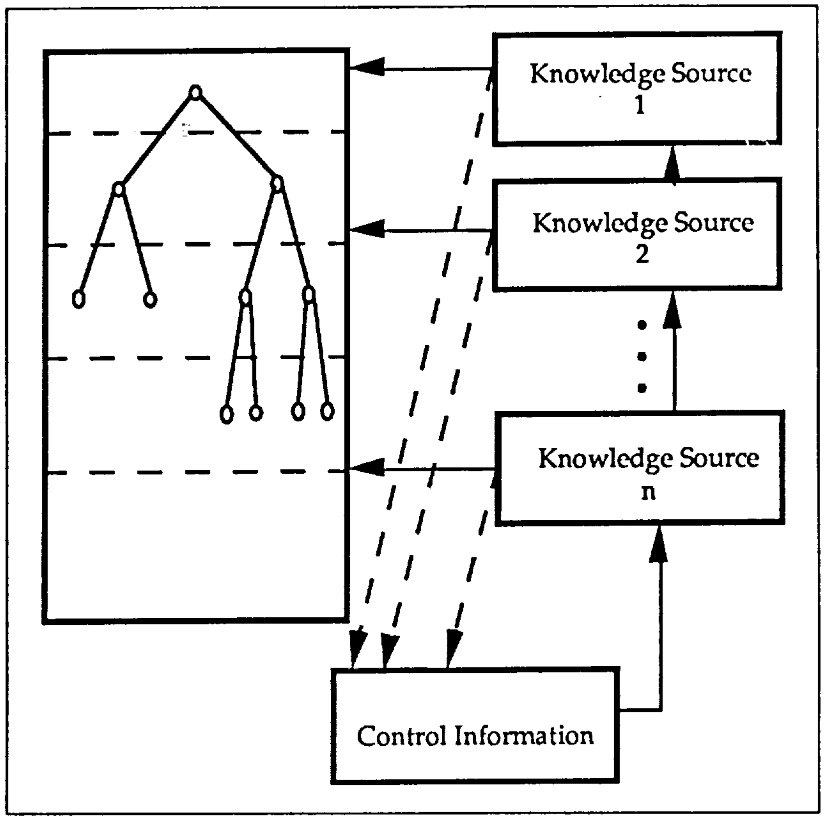


Fig. 16.1 Classical AI blackboard metaphor

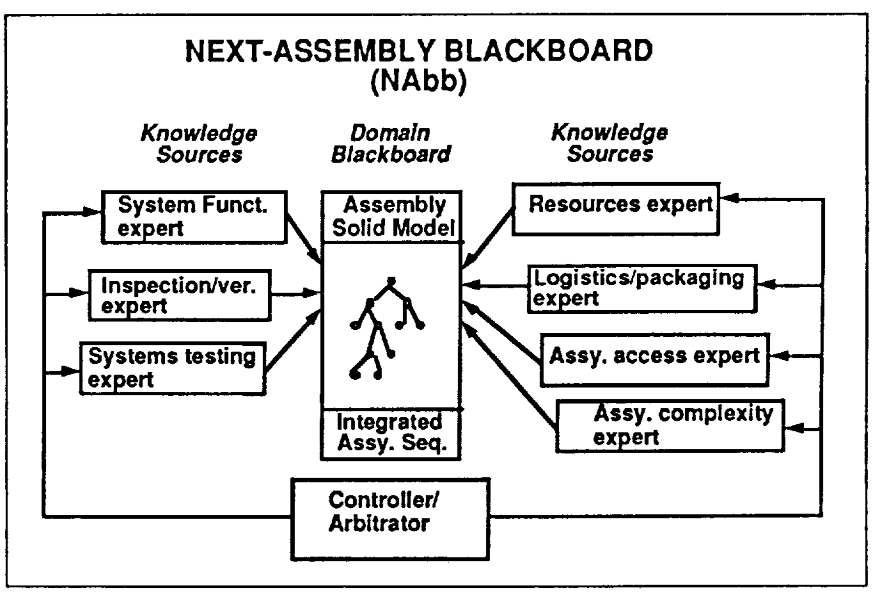


Fig. 16.2 Starting from a 3-D solid model, a feasible assembly sequence is formulated.

DEPLOYABLE STRUCTURES FOR SMALL SPACECRAFT

Martin M. Mikulas, Jr.

A trend towards the use of smaller launch vehicles for achieving science missions has grown during the last few years. This trend has been motivated by new advances in miniaturization and performance of electrical components, computers, and sensors which permit very small spacecraft to carry out significant missions. This fact, coupled with the failures experienced in large, very expensive spacecraft, is causing the science community to rethink how to obtain data from space in an affordable fashion. The science community is now thinking in terms of constellations of smaller spacecraft in lieu of single, large, expensive spacecraft. This new approach of doing business in space is causing the spacecraft design community to rethink the design methodology that has evolved over the past 30 years of space research. Currently numerous small spacecraft are being built and others being studied for future missions using the advances in electronic devices. Unfortunately, the mechanical and structural design of these small spacecraft has not kept pace with electronic advances. This is due primarily to the fact that the structures community has concentrated on the issues associated with relatively large spacecraft over the past fifteen years. Thus the mechanical and structural design technology being used in this new generation of spacecraft is essentially that developed 20 to 30 years ago.

In CSC, we are responding to structures and materials research opportunities, and challenges in the framework of this new generation of small spacecraft. Our response is focused on three primary areas: 1) design studies of representative launch vehicles and missions for small spacecraft, 2) low-cost, lightweight, advanced deployables, and 3) novel advanced composite structures.

CSC is considering three main categories of deployables for small spacecraft: 1) stored strain energy unfurlables, 2) inflatables, and 3) mechanically articulated deployables. K. C. Park and Gyula Greschik are working on a specific unfurlable deployable beam that deploys in a helical geometry to enable its integration with helical antennas as well as to enhance its stiffness. Martin Mikulas and Jeffery Goss are developing thin composites for general unfurlable deployable beams. In each category we are studying the technology limitations, and assessing high potential payoff areas for future research. In the past minimal consideration was given to cost, with the primary objectives being extreme reliability and high structural performance. The primary objective of our current studies is to conceive and develop deployable structures which are specifically suited for the low loading and stiffness requirements associated with small spacecraft. A major emphasis of this research will be to translate these low loading and stiffness requirements into very inexpensive, easy-to-fabricate structures.

A NEW LOW-COST UNFURLABLE COMPOSITE BEAM CONCEPT FOR SMALL SATELLITES

Martin M. Mikulas, Jr., Jeffery Goss

Over the past thirty years considerable research has been conducted on the development of deployable beam structures for various space missions. To date the bulk of the research has been on structures which require an external deployment fixture, for which cost was not a major concern. However, the string of recent spacecraft failures which continue to plague the aerospace community has led to a reevaluation and to renewed emphasis on "miniature" spacecraft to be launched on smaller, less expensive vehicles.

CSC has planned a new generation of structures based on an unfurlable truss beam that makes use of composite "carpenter-tape" members to eliminate mechanical joints and maximize simplicity. The expensive, unfurlable STEM and BI-STEM structures used in the past have low bending and torsional stiffness, and possess a relatively high coefficient of thermal expansion of the metal, causing significant distortion problems. The use of advanced composites for such applications would not only eliminate the thermal distortion problem, but also provide a weight savings.

Currently, a prototype of a four-longeron truss beam is being evaluated using wood for the batten planes and off-the-shelf steel carpenter tape for longerons and diagonals. The longerons and diagonals are buckled inward for packaging, resulting in a packaged height only slightly greater than the height of the stacked battens. When released, the beam deploys sequentially beginning with the top bay, due to the constant-force nature of the bent members. The beam demonstrates rapid deployment and a rather high deployed stiffness. We are now developing composite members to replace the steel and wood of the prototype.

Over the last few months, CSC has created analytical models of strength, stiffness, and deployment time. We are now performing tests on the prototype to verify the insights provided by the analytical models. Current tests include reaction forces conducted back to the spacecraft, buckling load, and deployment time.

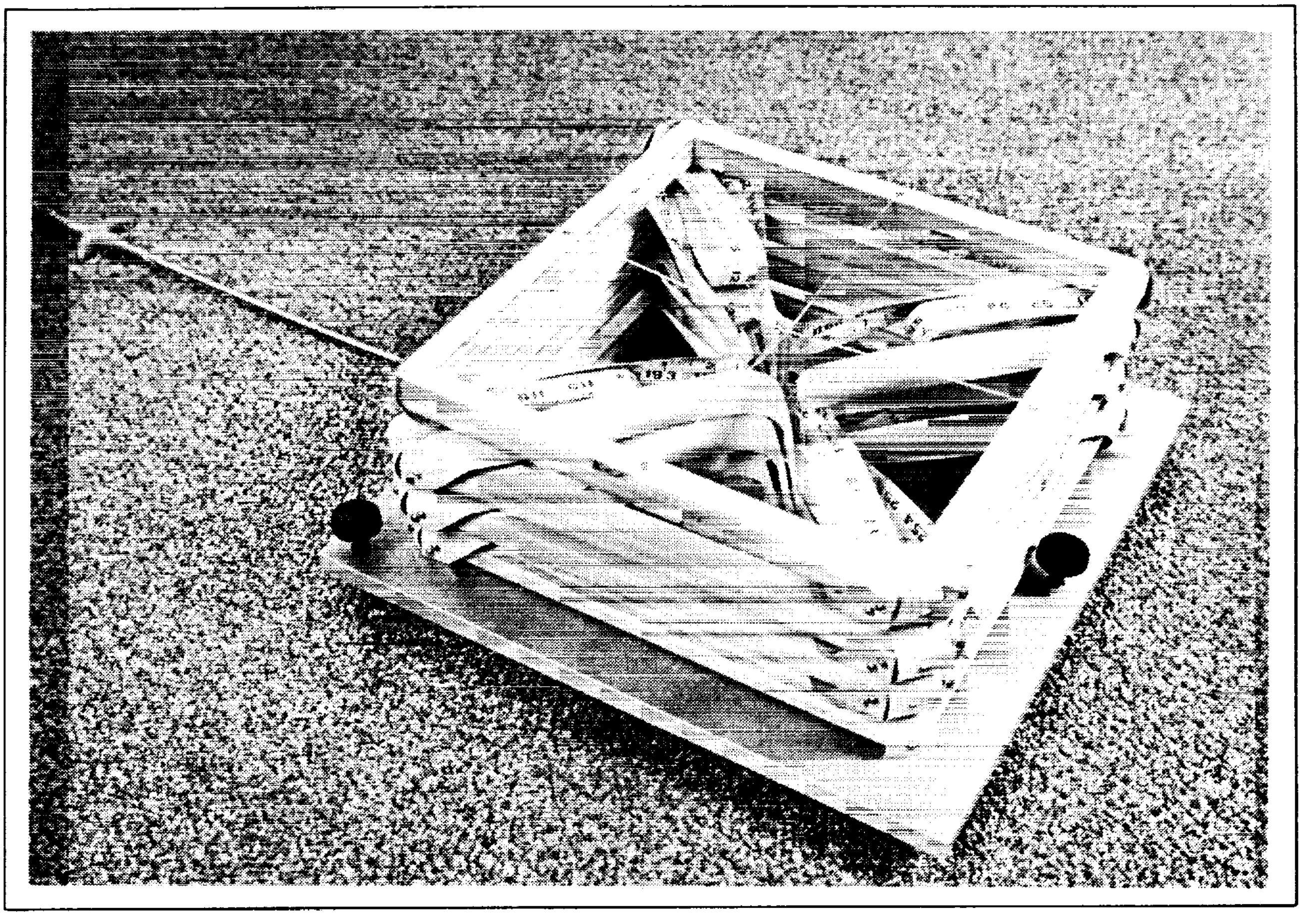


Fig. 18.1 Packaged prototype of curved longeron truss

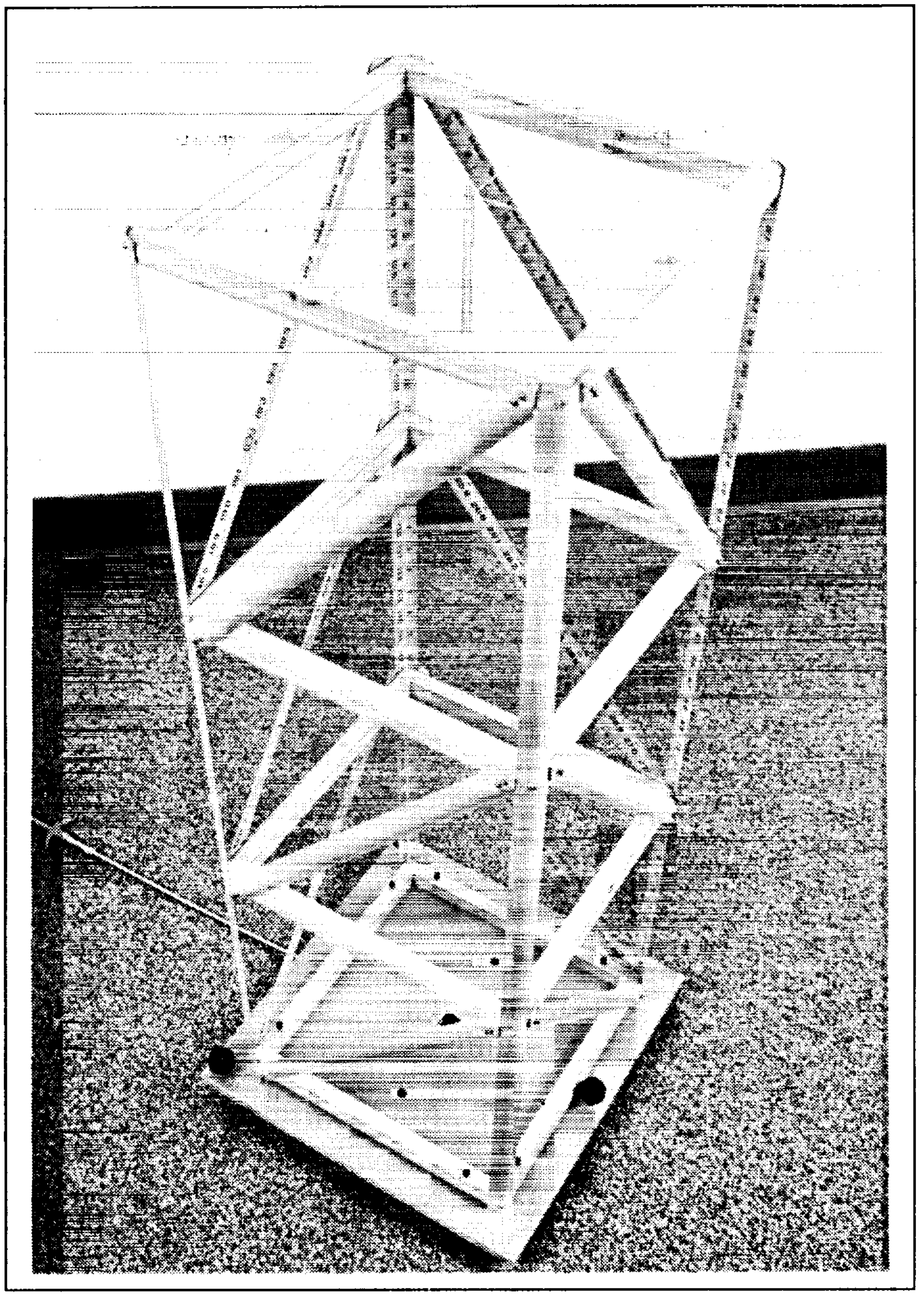


Fig. 18.2 Deployed prototype of curved longeron truss

LEARNING CONTROL FOR SMALL SATELLITES

Dale A. Lawrence, Penny Axelrad, François Padieu, Timothy E. Holden, Michael Malone, Jim D. Chapel

There is increasing interest in small satellite technology as a means to lower the costs and shorten the time scale for spacecraft missions. In this context, "small" can extend beyond physical dimensions, to include reduced-complexity missions, more automated design cycles, and increased on-board intelligence and autonomy for reduced mission ground support and increased reliability.

In particular, it is difficult to accurately predict spacecraft attitude disturbances such as aerodynamic torques, solar and earth irradiance torques, and residual magnetic moment torques before launch. Conventional attitude control systems provide precise pointing in the presence of these disturbances by providing large enough control authority to reject all disturbances within a certain amplitude envelope. This requires high authority actuators (e.g. reaction wheels), often with additional units for redundancy. For small satellites, this conventional approach is likely to require a significant fraction of overall spacecraft power, mass, and volume, limiting the ultimate size reductions and efficiency improvements of small satellites.

An alternative to high-authority attitude control is to accurately predict the disturbances, and control the spacecraft by supplying a corresponding "anti-disturbance". Here, actuation can often be supplied more efficiently—e.g. for low earth-orbiting spacecraft, magnetic control is often sufficient, even though it allows only two-axis torque at any instant. Variation in magnetic field over the orbital period provides the needed authority in all directions, provided this variation can be accurately determined. Since models for these disturbances and magnetic fields are not accurate enough to pre-program such anti-disturbance attitude control, an on-board learning algorithm is desirable. This algorithm continually refines an internal model of disturbances during each orbit, resulting in precise attitude control over the mission lifetime. Such a learning control algorithm shifts the burden of attitude stabilization to more "intelligent" algorithms in the flight computer, and away from bulky hardware. In addition, a reliable on-board learning capability reduces the need to simulate every worst case disturbance scenario, simplifying validation of attitude control system designs. This approach therefore holds significant promise for reducing the size and cost of small satellites.

The Center for Space Construction has begun detailed dynamic simulations of these learning controllers on small satellite buses, in conjunction with personnel at Orbital Sciences Corporation's Space Technology Laboratory in Boulder. The simulation is being developed in a MATLAB[R]/SIMULINK[R] environment, allowing relatively straightforward testing of different control algorithms, and simple analysis of simulation outputs. The simulation is currently configured such that an analytic orbit propagator is used in generating the environmental torques (aerodynamic, solar pressure, magnetic, etc.) and the control torques (magnetic torque rod actuators). The total torques drive the rigid body rotational dynamics (Euler's equations) and subsequently, the kinematic equations of motion. The spacecraft attitude is represented by means of a body-reference-frame to inertial-reference-frame quaternion.

The SIMULINK[R] environment allows simple modifications of the simulation for the testing of advanced learning control techniques. More conventional control methods for objective measures of sensor/actuator combinations can be tested by substituting appropriate blocks in the simulation. This initial simulation will be continually improved by refining the models in the constituent blocks. For example, the analytic orbit propagator may be replaced by orbital equations of motion, allowing more accurate evaluation of the influence of satellite attitude on satellite orbit. This simulation will provide a testbed for initial ideas in advanced control methods for small satellites, and an increasingly detailed evaluation of their suitability for practical spacecraft control.

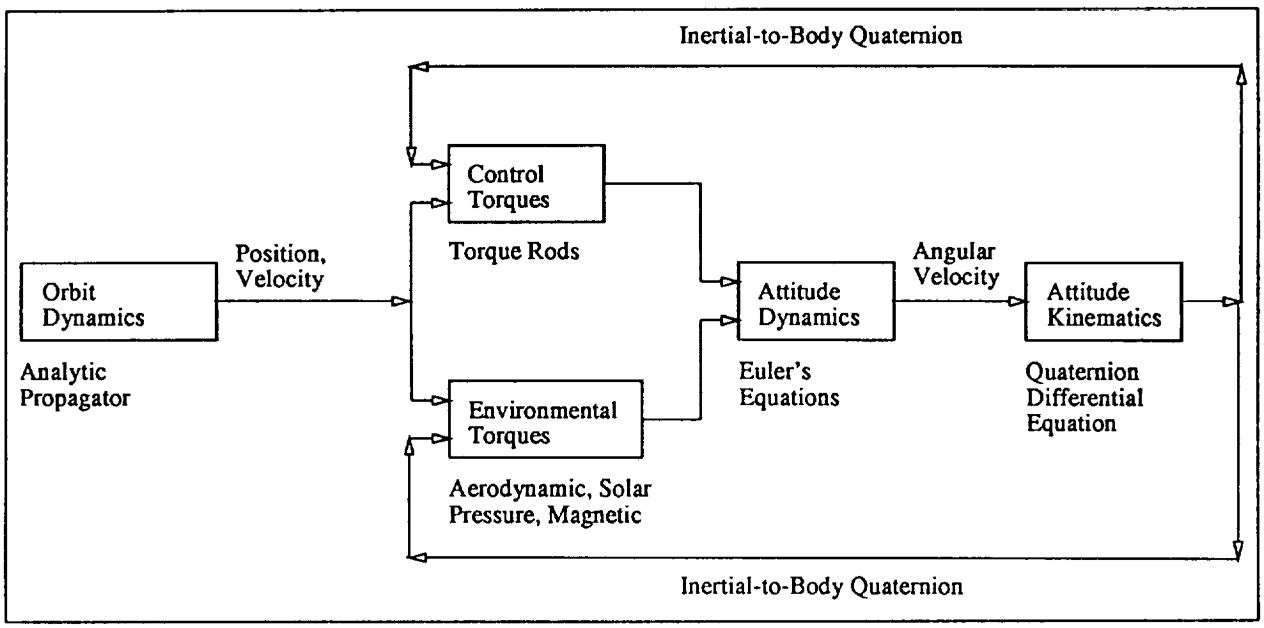


Fig. 19.1 The simulation block diagram shows how orbit trajectories are generated, then used to construct both disturbance (environmental) torques and control torques (via magnetic torque rods). The effect of these torques is determined by the spacecraft dynamics and attitude kinematics, resulting in a quaternion representing the attitude history relative to an inertially-fixed reference frame.

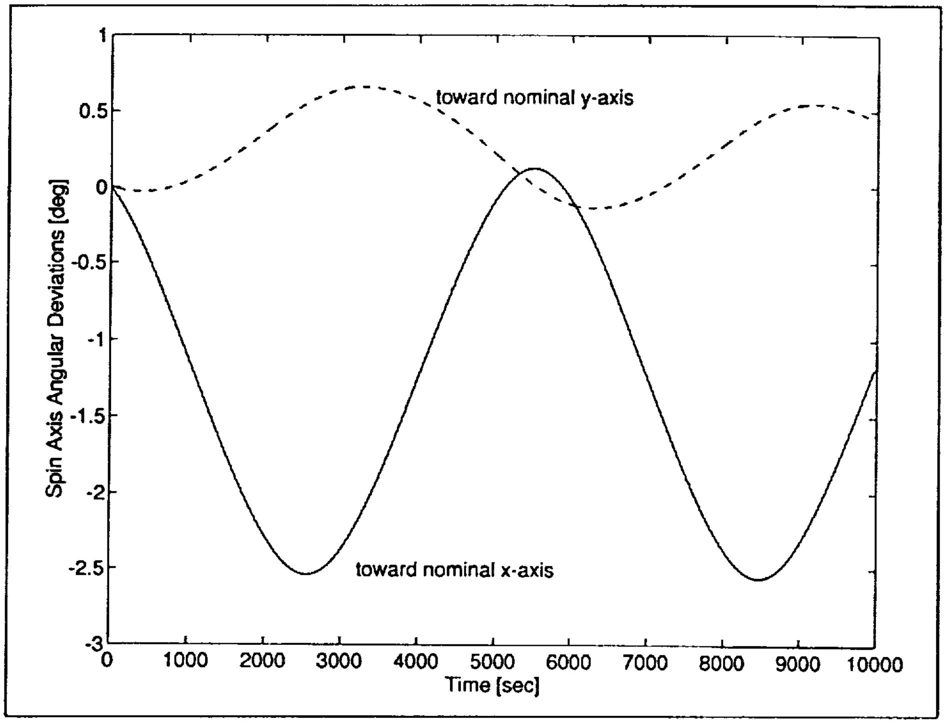


Fig. 19.2 The components of the geomagnetic field as the satellite progresses through its orbit (one orbit = 6000 sec) determine the magnetic control authority available at each point in the orbit. This case represents a circular sun-synchronous orbit at 750 km altitude.

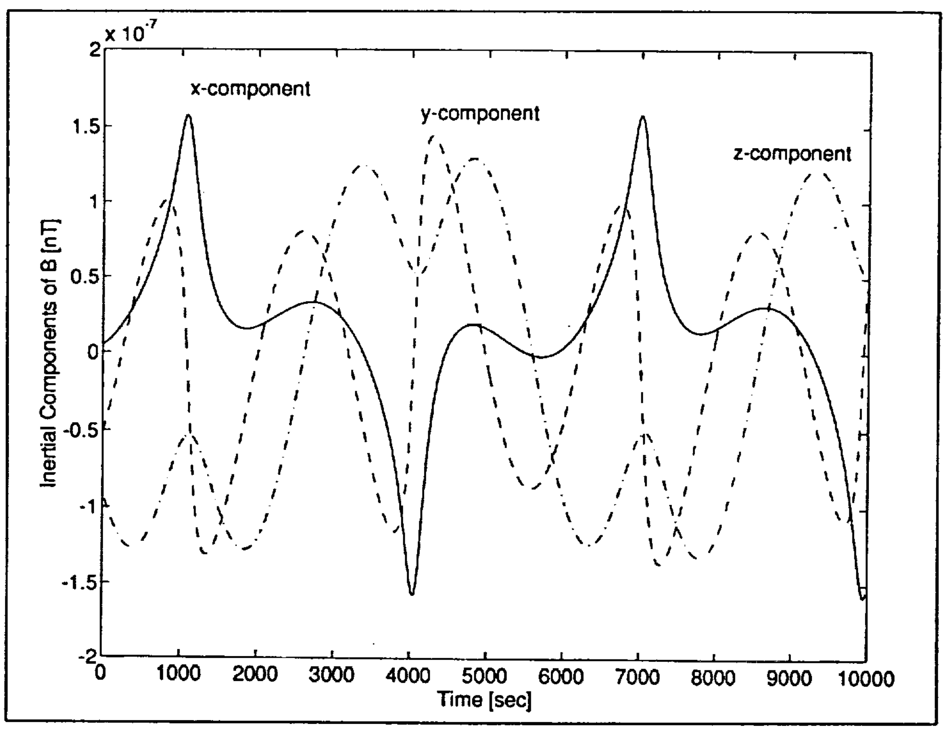


Fig. 19.3 Angular pointing error of the satellite relative to an inertially-fixed reference attitude due to aerodynamic disturbances. This open loop (no control) case shows reasonable angular deviation for low-accuracy missions. Learning control may be employed to improve this accuracy to satisfy a wider range of payload attitude stabilization requirements, with minimal increase in satellite complexity and cost.

LUNAR/MARS SYSTEMS

REGOLITH AND STRUCTURE-MEDIA INTERACTION MODELING

Stein Sture, Hon-Yim Ko, Frank Barnes, Ledlie Klosky, and Steven Perkins (Montana State Univ.)

Construction of lunar facilities must be based on optimum designs that use a minimum or economic combination of imported and indigenous materials, labor and energy. This engineering philosophy implies a precise understanding of the properties of regolith, equipment capabilities and behavior of constructed facilities in the harsh lunar environment. The design of embankments, excavated cuts, retaining structures, foundations and support systems typically relies on classical theories and analysis techniques for evaluating load-carrying capacities and deformation behavior. As explained in previous reports, lunar regolith, without glasses and agglutinates, possesses unusual engineering properties in that both strength and stiffness are highly density dependent. Cohesion, which derives mainly from particle interlocking and electrostatic forces, is significant in contrast to granular soils found on Earth and varies between 0 to 15 kPa. Interparticle friction, which derives from mineral-to-mineral surface friction, texture and fabric arrangement, typically varies from 38 to 60 degrees, and has a large influence on both strength and stiffness, in that a factor equal to or a function of the exponential of the friction angle is multiplied with the governing expressions. The density itself typically varies from 1.6 to 2.2 cubic centimeters.

The engineering properties of regolith are quite different from the soils on Earth for which governing theories and analysis techniques have been developed. Few verifications have been conducted in cases where the friction angle has been high and where cohesion contributes significantly to strength and stiffness. In a recent CSC centrifuge modeling effort our goal was to examine the validity of conventional approaches for lunar regolith. We conducted model bearing capacity experiments in the 400 g-ton centrifuge, where plane strain conditions were created by means of a segmented footing system having a scale width of 2 cm. Using a modeling-of-models scheme to study prototype behavior under 1/6-g, we have established that current theories and analysis procedures result in inaccurate results, especially at high friction angles.

In past years our regolith-property experiments were conducted with pure regolith simulant (Minnesota Lunar Soil simulant, MLS-1), which comprises a highly well-graded material of highly irregularly-shaped basalt particles. During the past year we have processed large amounts of MLS-1. We have initiated a test program in which we include in the pure regolith various amounts of both glass particles which simulate the microtektites present in the lunar soil, and agglutinates, which are highly irregularly-shaped welded agglomerations of glass and basalt, to study how or if these inclusions alter its engineering properties. It is well established that the regolith at some of the Apollo landing sites contains significant amounts of glass and agglutinates, and that the soil-composite appeared to exhibit different engineering properties. We are conducting conventional and unconventional confined triaxial tests to study the constitutive and stability behavior of the soil, and to examine how the properties are influenced by the glassy particles and agglutinates.

In order to understand the density profile of the lunar regolith we conducted an extensive series of scaled centrifuge experiments, in which the free-field soil model was subjected to motion similar to that generated by lunar quakes and impacts of meteoroids. These established that the in-situ regolith is quite dense, even near the surface, and that its density increases rapidly with depth. It has been speculated that this is due to the long-duration but generally low-intensity ground motion that has affected the moon for the past billion years. We have shown that the ground motion is the main cause of densification. We examined the density profile with a static sounding or penetration device, which was pushed into the regolith at constant speed, while resistance to penetration was recorded at the top. By means of pushing in and for short durations pulling out the probe at regular intervals, and using an inverse identification scheme, we obtained information on strength and density properties at several locations in the model. By these means we obtained profiles very similar to those obtained on the lunar surface, demonstrating the uniform development and consistent results of our models.

To enhance stability of regolith moving operations, vehicles and cranes, and gain additional strength in embankments and cuts, we have developed vibration-assisted auger and spiral penetrators, which can serve as anchors or reinforcement elements in construction. Equipment and vehicles handling large loads and antennas may require easy-to-install and easy-to-retrieve anchoring devices to help ensure stable and safe operation without having to resort to large masses. Steep embankments or excavated cuts in relatively dense regolith may remain stable if no disturbance occurs, but since the dense regolith is very brittle in addition to being strong and stiff, sudden failure may occur. To reduce risk and ensure safe and economic operations, we have found that the use of regolith-reinforcement elements or "soil nails" that are driven into the soil while being vibrated, will greatly increase ductility and stability.

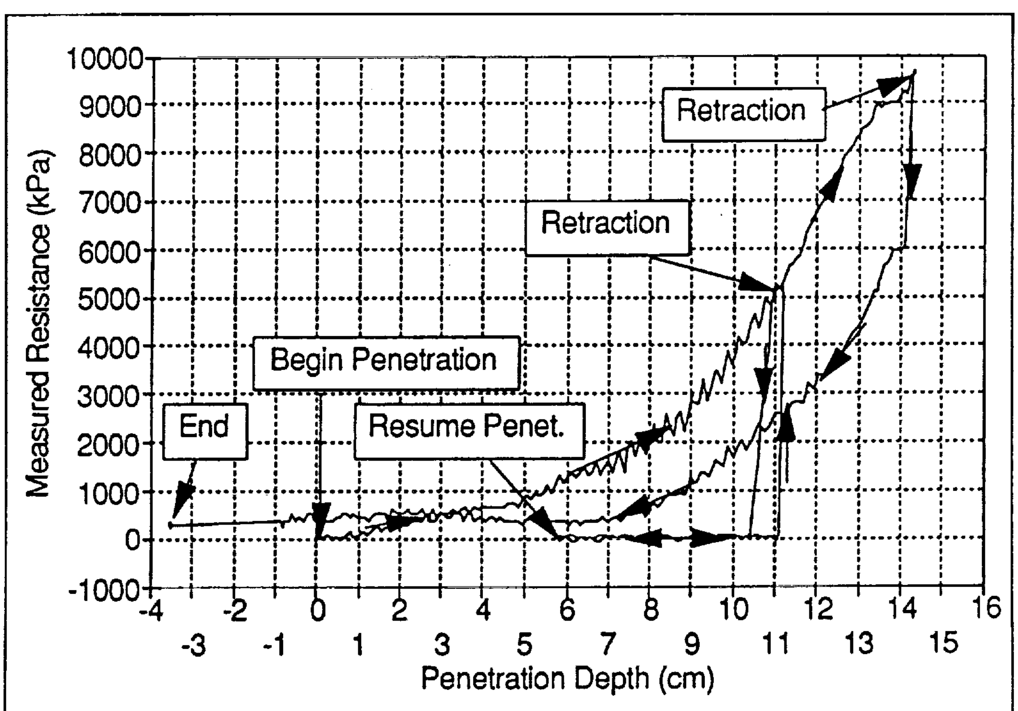


Fig. 20.1 Regolith resistance vs. depth

APPLIED VIBRATORY FORCES ON LUNAR SOIL SIMULANT ("LUNAR BULLDOZER")

Bela Szabo, Frank Barnes

CSC has designed and constructed a "lunar bulldozer" model system in order to study more efficient methods for digging and excavating lunar soil. The reasoning for designing a new type of bulldozer was to decrease the amount of mass and energy needed to send to the moon, therefore minimizing the cost of equipment and operations. Experimental results have shown that applying vibrational forces at the blade cause significant reductions in the horizontal force required to move the bulldozer in the regolith. This suggests that the vibrating blade fractures the soil matrix, reducing its cohesiveness. The frequency dependency of the soil resistance indicates that the mechanical power delivered to the soil is also a function of the frequency. The frequency where the soil resistance is minimized is the desired operational frequency of the bulldozer.

During the past year we further developed CSC's lunar bulldozer testbed system. The bulldozer system is an integrated system of hardware and user interface control and analysis software (Figure 21.1). The mechanical "bulldozer" includes a carriage, a vibrating blade and a steel box containing lunar soil simulant. Also, in the past year we have implemented a software-driven control and data acquisition system as well as an object-oriented user interface. The software designed to control the actuators, acquire sensor information and analyze data for the lunar bulldozer was written in LabVIEW^R. LabVIEW^R is a software environment for designing both the user interface and back end for real-time data acquisition and control systems. To control and analyze the system, we developed "user-friendly" virtual instruments in LabVIEW^R. Virtual instruments are self-contained software programs that can perform either software or hardware operations and be controlled through an "instrument panel-like" user interface (Figure 21.2).

Our preliminary studies have shown that when blade vibration is applied, the drive force will drop considerably from the static case. By breaking up the soil using the small amplitude blade vibration, the amount of workload on the drive motor is decreased. Furthermore, changing the frequency of the blade vibration changes both the force of the soil on the blade and the mechanical power delivered to the soil. Hence a resonance curve is obtained by scanning the blade vibration frequency over the bandwidth of the blade actuators. A very significant increase in drive force can be seen at the points where the blade actuators are turned off. This corresponds to a surprising reduction in drive force of six to ten times, when using blade vibration. Also, the drive force acted slightly differently for each of the frequencies. (Figure 21.3). Currently, part of our focus is to gather sufficient data to characterize the resonance effect of the lunar soil simulant. Also, the effectiveness of the system is studied with different types of terrestrial soils to establish a metric for comparing the lunar bulldozer with existing terrestrial bulldozers. The importance of this comparison is that it will provide a way of specifying the possible advantages of "lunar bulldozers" for both lunar and terrestrial applications. In addition, we are currently designing a new bulldozer hardware system. We are developing this system to test the effects of several different linear vibratory motions on the soil force.

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BLACK AND WHITE PHOTOGRAPH

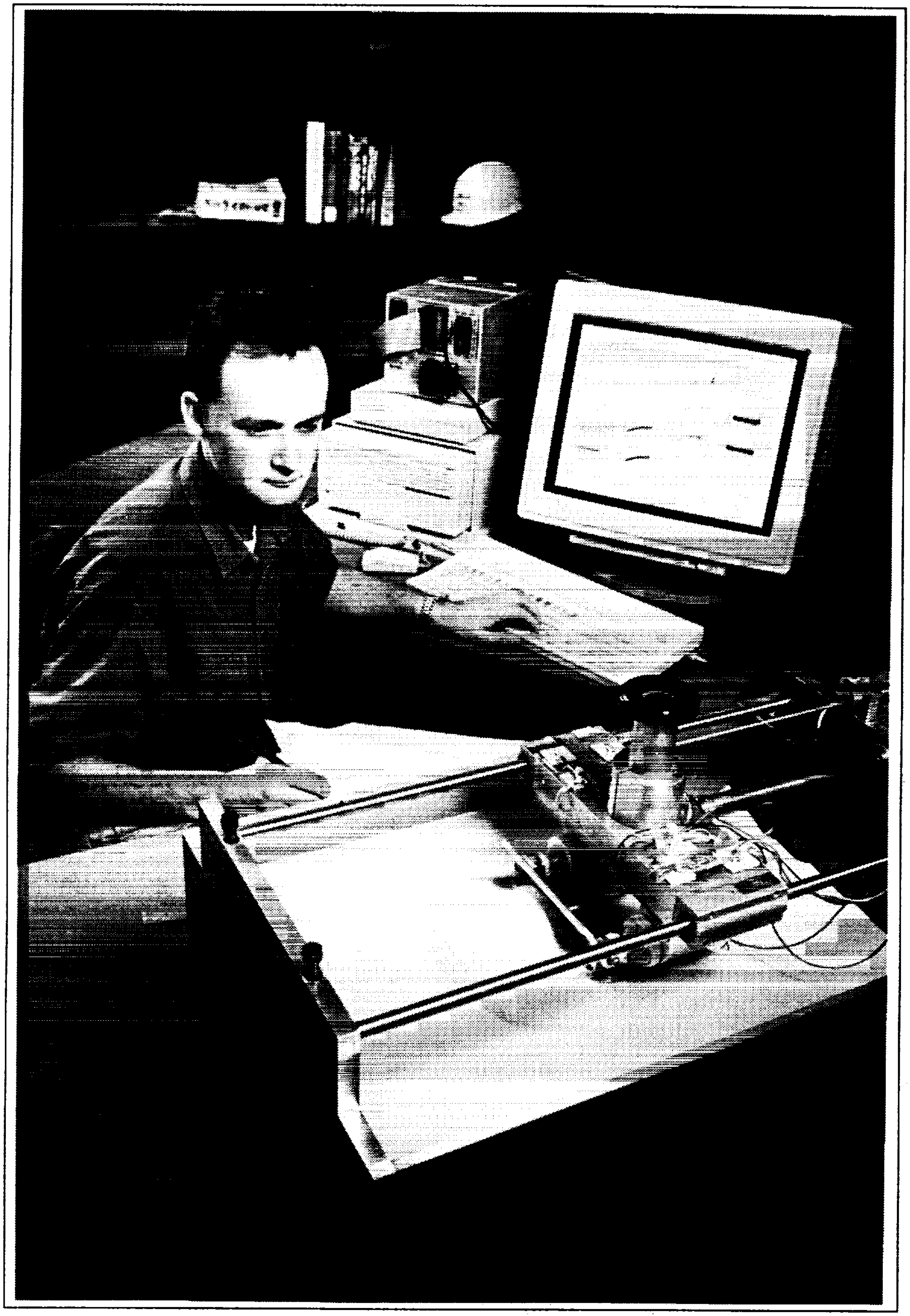


Fig. 21.1 Integrated "lunar bulldozer" system

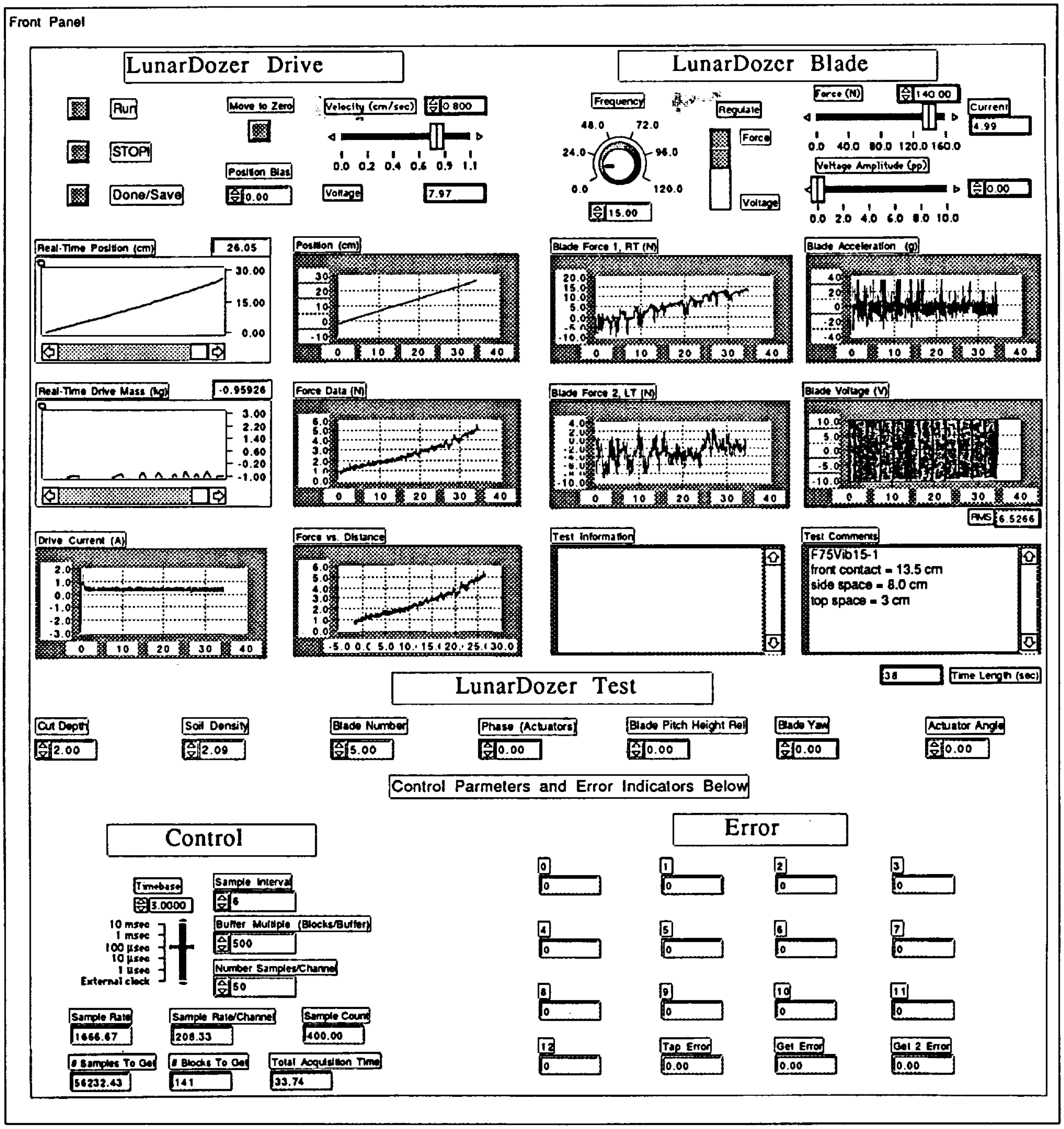


Fig. 21.2 "Lunar bulldozer": user-interface control panel

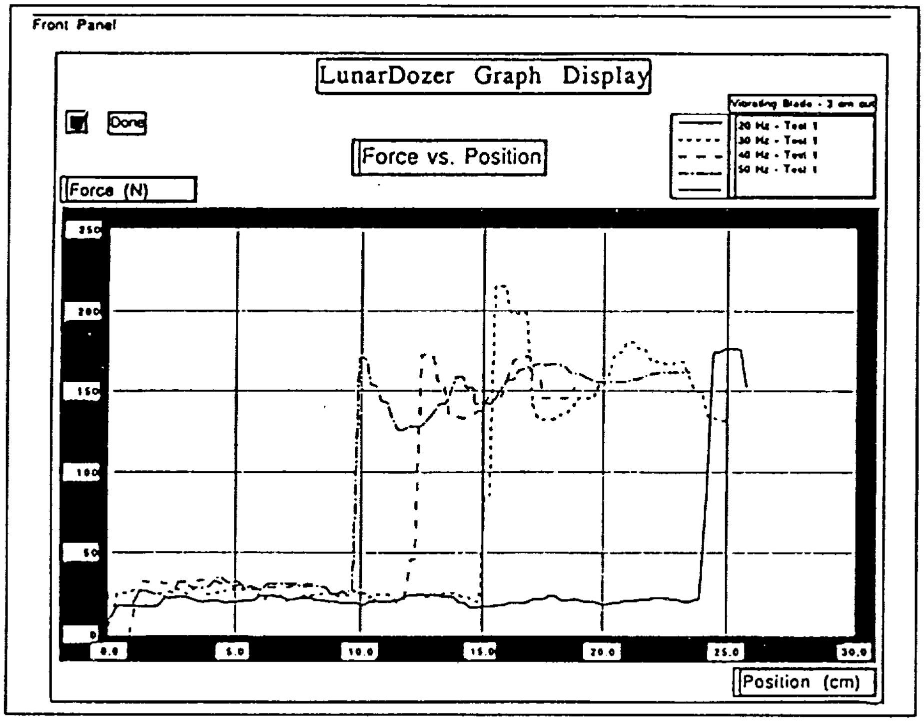


Fig. 21.3 Resonance curve of lunar soil

ANALYSIS AND DESIGN OF A LARGE LUNAR CRANE

Robert Taylor, Martin Mikulas, and John Hedgepeth (Adjunct Faculty)

Several conceptual studies on lunar base development have addressed the global issues and provided straw-man designs for achieving a permanent manned presence on the moon. Numerous distinct technologies must be researched and developed to realize these designs, including nuclear or solar power systems, habitation modules, thermal dissipation systems, and construction methods. The focus of this research is one specific task, the problem of unloading and integrating multiple-lander payloads. This task requires new specialized lifting equipment. It has been shown that the most efficient means of meeting this requirement is a large specialized robotic crane. The crane must meet a different set of operational requirements than conventional cranes. Conventional cranes are often much heavier than the payloads they maneuver and rely on ground personnel to guide the payload into position. A lunar crane would have to autonomously lift and control a payload many times heavier than the crane itself, which can only be accomplished with a suspension system which uses multiple links between the boom and payload.

The primary conceptual design under consideration and study is the two-cable, six-link suspension system. This system uses a single lifting winch to control two cables that pass through pulleys to provide six links between the boom and the payload. The suspension system is used with a cross-shaped payload boom. Instead of the single hook used on conventional cranes, this system uses a triangular end-effector platform. The platform is attached by a rotary joint to a payload grappling attachment. The two cables pass over the end of the boom, where they split and descend to either front corner of the platform, pass around pulleys, ascend to the ends of the T-boom, pass around a second set of pulleys and descend to a common attachment point at the back corner of the payload platform as shown in Figure 22.1. A concept for using this suspension with a cargo lander as the base support is shown in Figure 22.3. The cable arrangement provides six preloaded cable links between the crane boom and the end-effector platform in a Stewart platform-type arrangement. The pulley use is similar to a "block and tackle"-type lifting rig except that the pulley blocks have been separated to different locations. All four pulleys have two free degrees of rotation to allow alignment of the pulley with the cables as the platform travels up and down. A coordinate system is defined for convenience with the z direction vertical, the x direction lying in the horizontal plane in the direction of the boom, and the y direction aligned with the cross boom.

The basic operation of the six-link system is similar to the operation of a conventional boom crane. A single winch is used to reel in both cables simultaneously, lifting the payload in the z direction. The payload is moved in the y direction by swiveling the crane about its base. The payload is moved in the x direction by changing the boom angle and adjusting the main winch to keep the payload at a constant elevation. The angular orientation of the payload about the x and y axes is determined by static equilibrium of the cable system, which can be changed by moving the attachment points on the payload platform. The payload platform is always aligned in the direction of the boom, so a rotation joint between the platform and the payload allows the z-rotation of the payload to be controlled through 360°. Since all six degrees of freedom of the payload are controlled, the payload can be placed at an arbitrary location within the reach of the boom and the constraints of the linear actuator strokes.

The kinematics and dynamics of the six-link system have been investigated with the pulleys in two configurations, locked to provide a stiff system for translation of the payload and free to allow lifting the payload or changing the boom angle. A linearization of the pulley mechanics was derived for a pulley idealized as a single point in space connected by two lengths of cable which can pass through the pulley point. This linearization was used in a finite-element routine to obtain the natural frequencies of the system. The results show the effect of changing different parameters of the system design, including the boom size, payload platform size and height to which the payload is raised. Figure 22.2 shows a representative plot of the lowest six vibration frequencies of the free-pulley system for a baseline lunar crane model with a change in the size of the payload platform.

The approximation of a pulley as a point in space results in an error in either the direction or the length of the cables from the real system. This is due to the fact that with a finite size pulley, the two free sections of cable contact separate points in space. For the study of real suspension systems with large pulleys to prevent cable damage, this approximation could significantly affect the natural frequencies and behavior of the suspension. To investigate the possibility of a significant error due to the approximation of the pulley as a single point, a new linear model of the pulley mechanics has been derived, simulating a pulley disk of finite radius and a length of cable wrapped about it in three-dimensional space. Figure 22.4 shows the configuration of the finite-size pulley.

Although the basic frequency characteristics of the two-cable, six-link system have been investigated, we have not determined how to design or operate the suspension so that it will perform its task as efficiently as possible. This requires a metric of performance which will reflect increased utility in the lunar construction scenario. Because of the low-gravity, large payload masses and the requirement that the crane be of minimal mass, it is clear that any lunar crane design will have very low vibration frequencies of around 0.1 Hz. This means that all operations will be carried out slowly. Although a robotic construction scenario can allow long assembly times, reduction of the time required to perform a given task will speed assembly, thereby requiring less equipment, operator and maintenance time. Therefore the measure of performance proposed is the amount of time required to perform the translation of a payload. The time would include any wait period for the residual vibration to damp below a set level. This measure is chosen because it is the primary step in any payload integration and it is dependent solely on the design of the crane. Other steps such as grasping the payload or aligning the payload for docking depend on the hardware design of docking subsystems. The goal of our future research is to determine how to optimize the two-cable, six-link system with this definition of performance.

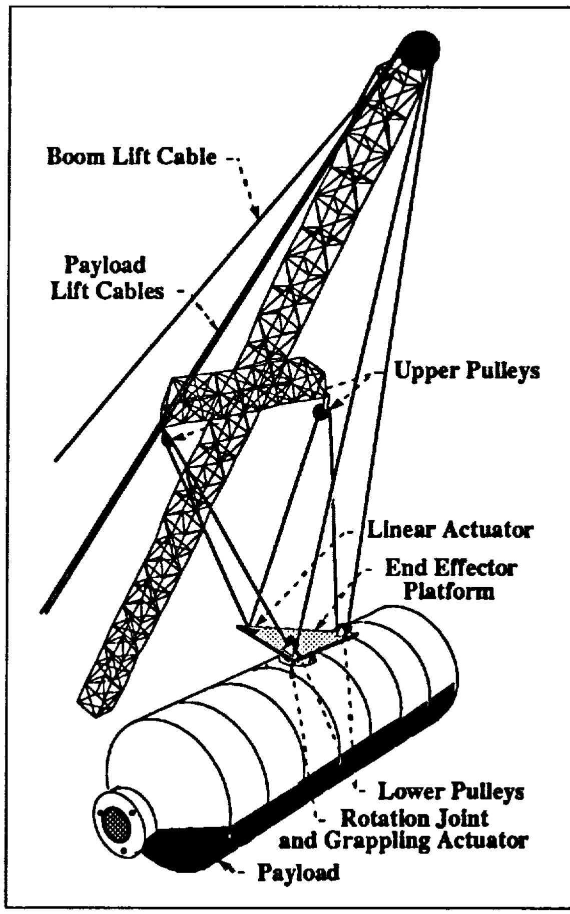


Fig. 22.1 Two-cable, six-link suspension

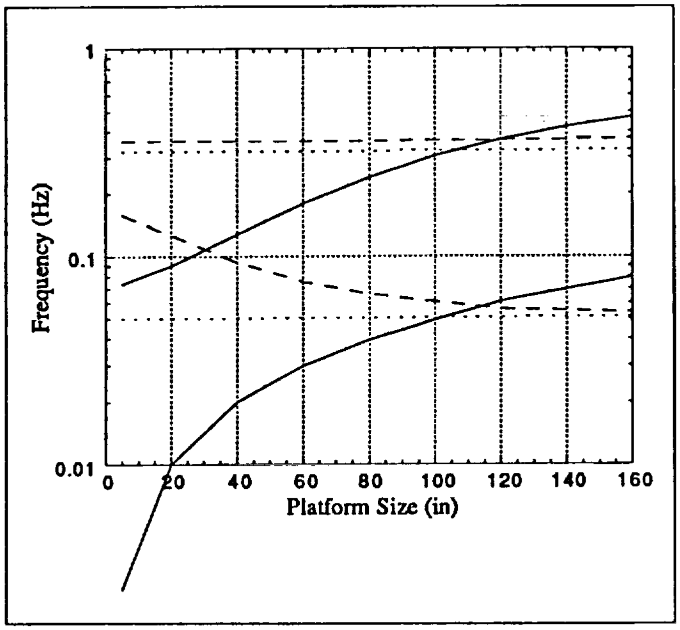


Fig. 22.2 Lowest natural frequencies of two-cable, six-link suspension

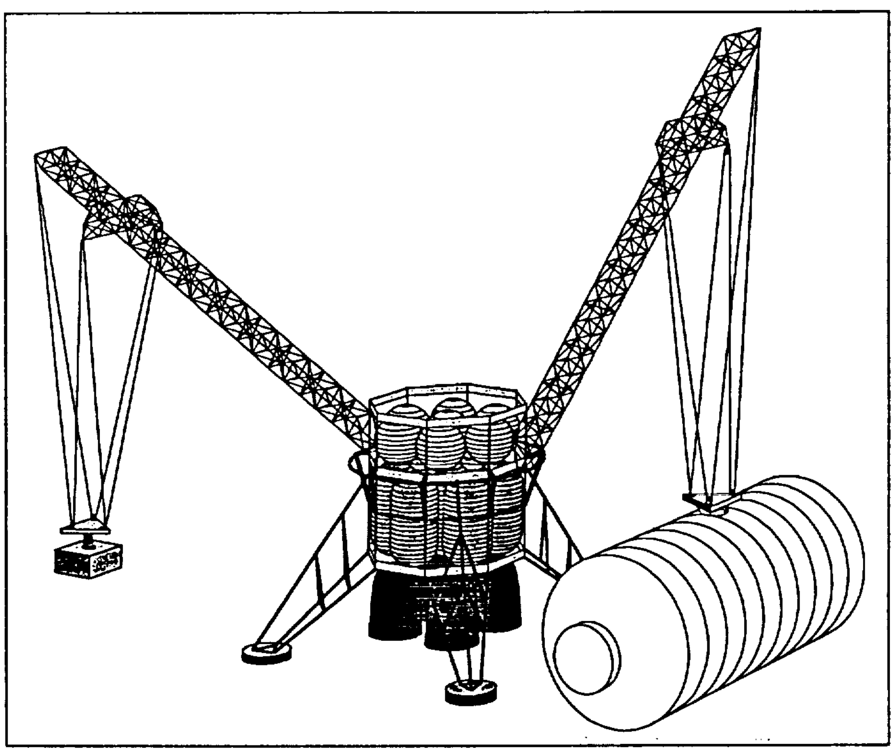


Fig. 22.3 Cargo lander with twin-boom crane

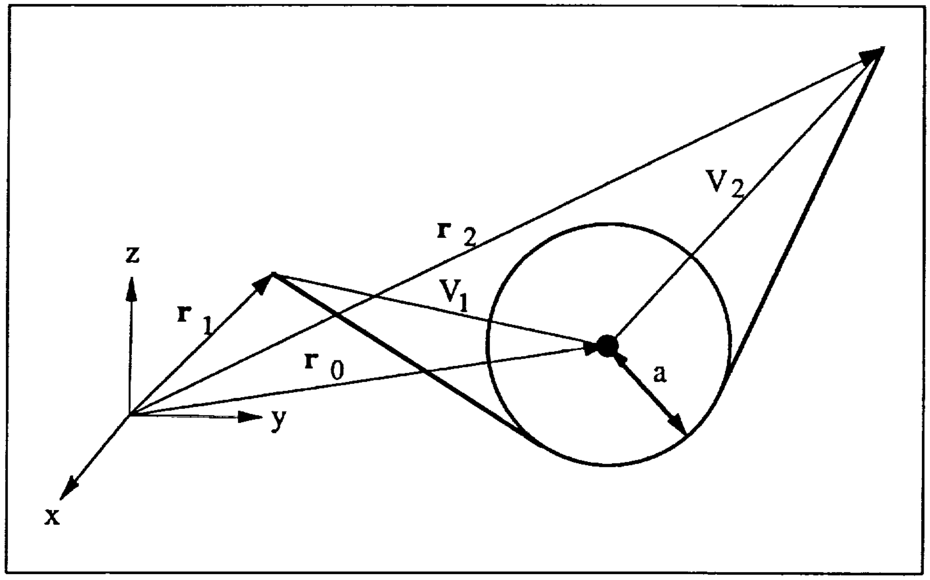


Fig. 22.4 Finite-size pulley

A RESEARCH TESTBED FOR OPERATIONS AND CONTROL OF DISTRIBUTED SYSTEMS

Chris Grasso and Renjeng Su

The tremendous advancement of many subsystem technologies such as microelectronics and sensors promises to lead to similar advances in the operational capabilities of future space systems. Operation and control of satellites with a large number of modes, and cooperating robots in an uncertain environment are prime examples of such future systems.

Distributed communication and control systems with sophisticated software allow an unprecedented level of on-board machine intelligence and man-machine interactions. The extremely complex software systems which handle both the operation and control of the space system and its communications with external control stations will be hybrid in nature, including both logical and numerical algorithms, and driven by both symbolic commands and numeric signals.

The state of the art of design and verification of such systems is still in its infancy. While the industry continues to develop products of great complexity, there is an increasing need for systematic methods for solving the following technical problems: How can we model the the system under development for design trade-offs and design integration? How can we verify a software system? How can we formally define the concept of modes and how can we design mode switching? How can we design various sorts of synchronization? How can we discover the undesirable states of the system and prevent their occurrence?

In 1991, the Center for Space Construction began to build a set of mechanical rovers as a research testbed for investigating these issues. This effort is now complete. The testbed consists of three autonomous rovers. It has demonstrated the capability of implementing distributive control among separate, local entities acting in a synchronized fashion. The testbed links together four levels of control, from basic motor operations up to ensemble control. The underlying control architecture features rationalized software interfaces and computing power, and appropriately distributes task responsibilities among the components of the system. The architecture is hardware-independent, and could be generalized to operate distributed systems like satellite constellations.

Key features of the testbed include:

- component-level modularity
- system-level redundancy
- standardized software and connection interfaces
- four different control locuses: low-level motor, component, vehicular, and ensemble
- decision-making capabilities to handle nonlinearities
- teleprogrammed device operation, rather than teleoperated operation
- synchronization events, with local compliance
- use of behavior bounding parameters with local and global supervisors monitoring for violations.

In these rovers, circular, mobile platforms provide power and movement capabilities for their attached components. Linear manipulators capable of lifting test modules are fitted aboard the bases, but have their own computing resources and controls. Components aboard the same base communicate over a twisted-pair ethernet-style local area network. Sensors can be tied to this network. A radio-frequency modem allows components to communicate offboard from the base to other rovers or to the human operators.

In the last year, a number of improvements have been fitted into the testbed. The visual positioning system is now on line, interfacing to the full system through the local area network. It scans for coded dot patterns on the vehicles, providing components in the system with calibration marks to prevent long-term degradation in perceived position. Printed circuit board implementations have improved the reliability of low-level motor control, and have eliminated several failure modes. Undervoltage detection is ready for incorporation into the mobile platforms. Control laws which improve the stability at the local control level are in place. A full, multipacket version of the local area network software has been installed in all components. A graphical user interface is approaching completion. These hardware upgrades will facilitate the study of open issues.

Currently the testbed is being used to study a number of specific issues. These include the distribution of local and global control, creation of control locus descriptions, teleprogramming techniques for use with ensembles of devices, and the effects of time delay in teleprogrammed event synchronization. The techniques for addressing these issues borrow heavily from software engineering for large programming systems. The application of software engineering to this problem domain is facilitated by the object-oriented design inherent in the control architecture.

Fig. 23.1 Global control: human user asserting supervisory control over ensemble of devices, with two rovers working in cooperation to move a module

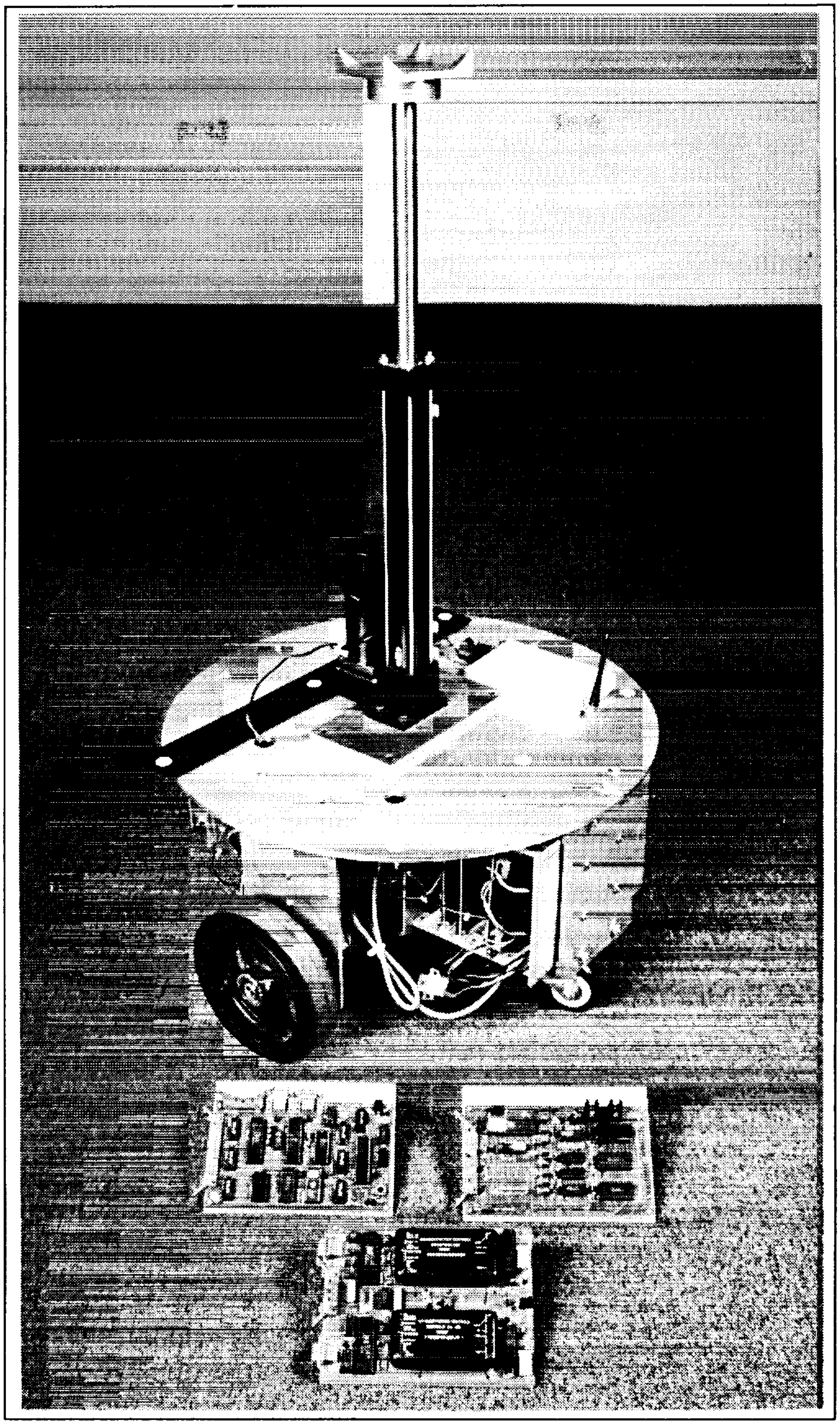


Fig. 23.2 Local control: base subsystem from rover, showing computer, local area network card, and motor control card

INVERSE KINEMATIC SOLUTIONS FOR REDUNDANT MANIPULATORS

Christopher E. Steffen, Renjeng Su

Remotely-controlled dextrous manipulators which can be used in space construction should:

- be modeled on the human arm and hand for ease of remote command and control (Figure 24.1),
- have a large, singularity-free workspace to simplify trajectory planning,
- have an inverse kinematic solution (IKS) solvable in real time at a rate greater than 30 times per second,
- be built using lightweight, high-torque, and low-power actuators, and
- be able to be controlled with discrete events as well as numerical commands by distributed hybrid control systems.

In this project we focused on the first three of these qualities: we first tried to identify manipulators which possessed the first and second characteristics, and next solved the IKS for the manipulators identified.

The "Dextrous Arm with Omni-Hand" and the "Dextrous Arm with Omni-Wrist", products of Ross-Hime Designs, Inc. are two commercially-available manipulators which possess the first two characteristics listed above. After identifying these manipulators we used their specifications to solve the design problems for four classes of manipulators. These were:

a) the PUMA arm with double-universal wrists,
b) the dextrous arm with omni-hand/three-intersecting-axis-wrists (Figure 24.2),
c) the dextrous arm with omni-wrist (Figure 24.3), and
d) the three-intersecting axis shoulder, pitch elbow and omni-wrist.

There are nine manipulators in each of the classes (b), (c) and (d). We completed the IKS for all of them. These manipulators can independently command wrist orientation, wrist position, and elbow rotation.

There are three manipulators in class (a). We solved the IKS for all three. These results will allow industry users to retrofit their existing PUMA manipulators with double-universal wrists. The approach eliminates wrist singularities and thus simplifies the problem of trajectory planning. Moreover, it increases the workspace of PUMA arms.

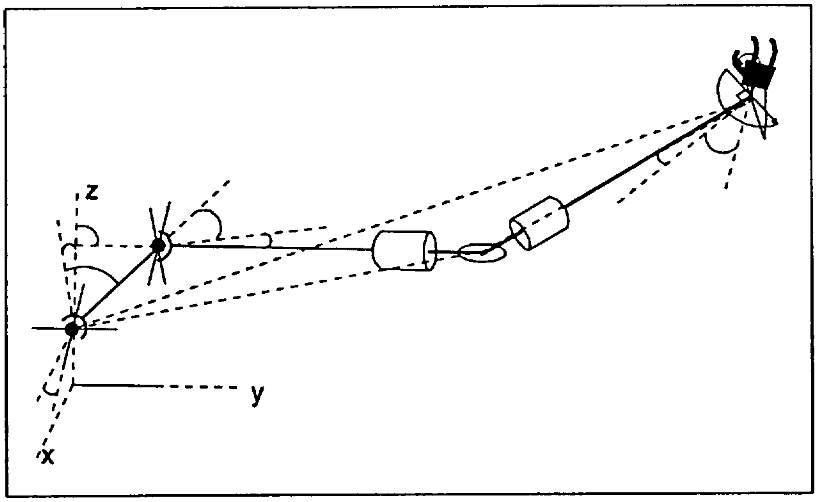


Fig. 24.1 Human arm model: ball and socket joints

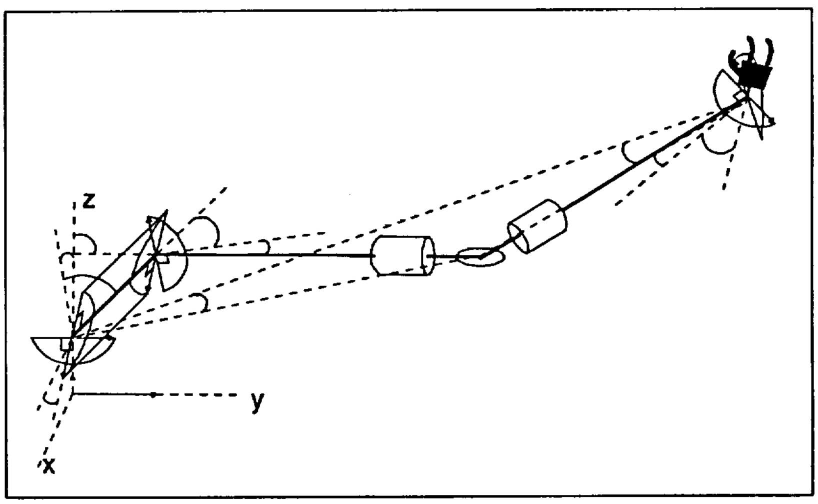


Fig. 24.2 Double-universal shoulder, pitch elbow, and three intersecting axis wrist

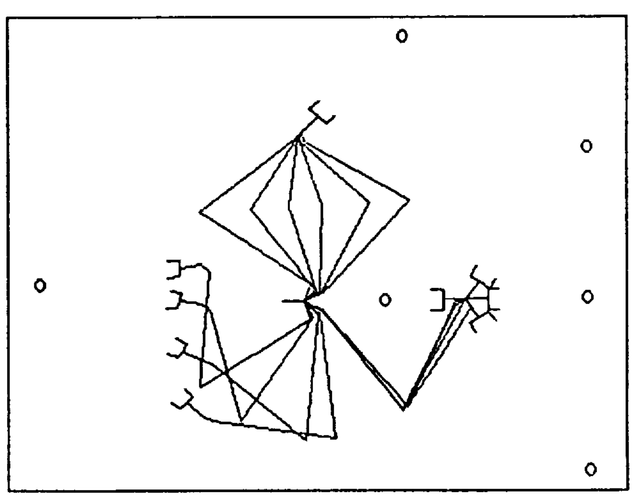


Fig. 24.3 Motions of the double-universal arm, pitch elbow, and double-universal wrist

EFFICIENT PATH-PLANNING STRATEGIES

George W. Morgenthaler, Kevin Gifford

Efficient path-planning for surface rover vehicles on the lunar or Martian surface is necessary due to the extreme cost of delivering mass/energy to a remote planet. Path-planning, in general, is the process of making decisions concerning vehicle speed and direction based upon available data. Path-planning for autonomous vehicles consists of three major functional areas; 1) the physical hardware that will control the autonomous vehicle; 2) definition of the local topography which may come from either *a priori* sources (such as a mapping satellite), or from *in-situ* sources (an on-board surface imaging system); and 3) software algorithms and associated computer hardware that will process the input data and generate output signals to control the speed and direction of the vehicle (see Figure 25.1). At the Center for Space Construction we have concentrated on the latter area in an effort to minimize as much as possible the energy that a rover vehicle would expend.

CSC is currently in the process of developing an efficient path-planning strategies (EPPS) system which makes use of three primary concepts:

- Mathematical tractability of minimum energy paths;
- Drag function estimation via analytical terrain/vehicle modeling concepts;
- Intelligent graph-searching via dynamic programming with expanding frontiers.

Using the calculus of variations, CSC has developed a repertoire of algorithms that will compute the minimum energy path between a known starting point and a known destination point where the surface soil characteristics between the two points can be modeled by a drag function $d(x,y,z)$. Figure 25.2 depicts the minimum energy paths for a drag function of the form $d(x,y,z) = kx^n$ where n ranges in value from zero, indicating a constant drag function—which can represent a dry hard plain—to increasingly higher exponents indicative of sandy or muddy soils requiring a greater amount of energy to traverse. Figure 25.3 shows that for differing soil regions a substantial energy savings may be realized by choosing the minimum energy path over the minimum distance path.

The determination of the surface soil characteristics is an important key to accurate computation of minimum energy paths. Various individuals and institutions have frequently modeled soil characteristics. Typical soil characteristic parameters used in the estimation of the drag function are wheel sinkage, gross tractive effort, compaction resistance, and total motion resistance. These empirically-computed characteristic parameters are dependent upon the physical characteristics of the soil (soil consistency, frictional and cohesive modulus of deformation, internal friction angle and soil slippage) and upon the physical characteristics of the tires (width and length of tire chord ground contact, wheel load and wheel footprint area). CSC has adapted the sophisticated vehicle/soil interaction models that were the output of this research and can now simulate these results via computer. The results can then be used to determine appropriate surface drag functions for differing types of soil.

With the ability to estimate accurate drag functions and a comprehensive set of algorithms that will compute the minimum energy path for all scenarios likely to be encountered, the problem of finding efficient energy paths as a surface vehicle travels from a known starting point to a known destination then becomes an exercise in graph-searching. For a graph search of a three-dimensional terrain region, one must have high-resolution topographical data along with soil data characteristic of the region. The cost function for the graph-search is made up of three components: traversability, safety, and energy. Traversability deals with whether a vehicle can travel across a given region of terrain. Safety considers the question of whether the traversing of the terrain will damage the vehicle or injure any of its crew. Energy considerations deal with the question of how far a vehicle can travel before needing to return or to refuel or recharge.

CSC is in the process of developing a graph-searching method to be used by the EPPS system that will be a variation of current dynamic programming algorithms. This variation makes use of dynamic programming techniques along with the concept of expanding frontiers. Dynamic programming supplies a multi-stage decision process that, as the algorithm progresses through optimization procedures, decreases the number of possible decisions (or paths) until an optimal path is found.

Future work in this project area for the Center for Space Construction will be primarily in the integration of the three concepts of energy path minimization, surface drag function modeling and intelligent graph-searching via dynamic programming to form a practical path planning package that will be of use in the control of autonomous surface vehicles on remote planets and also will save energy and time when equipment is used in planetary base construction.

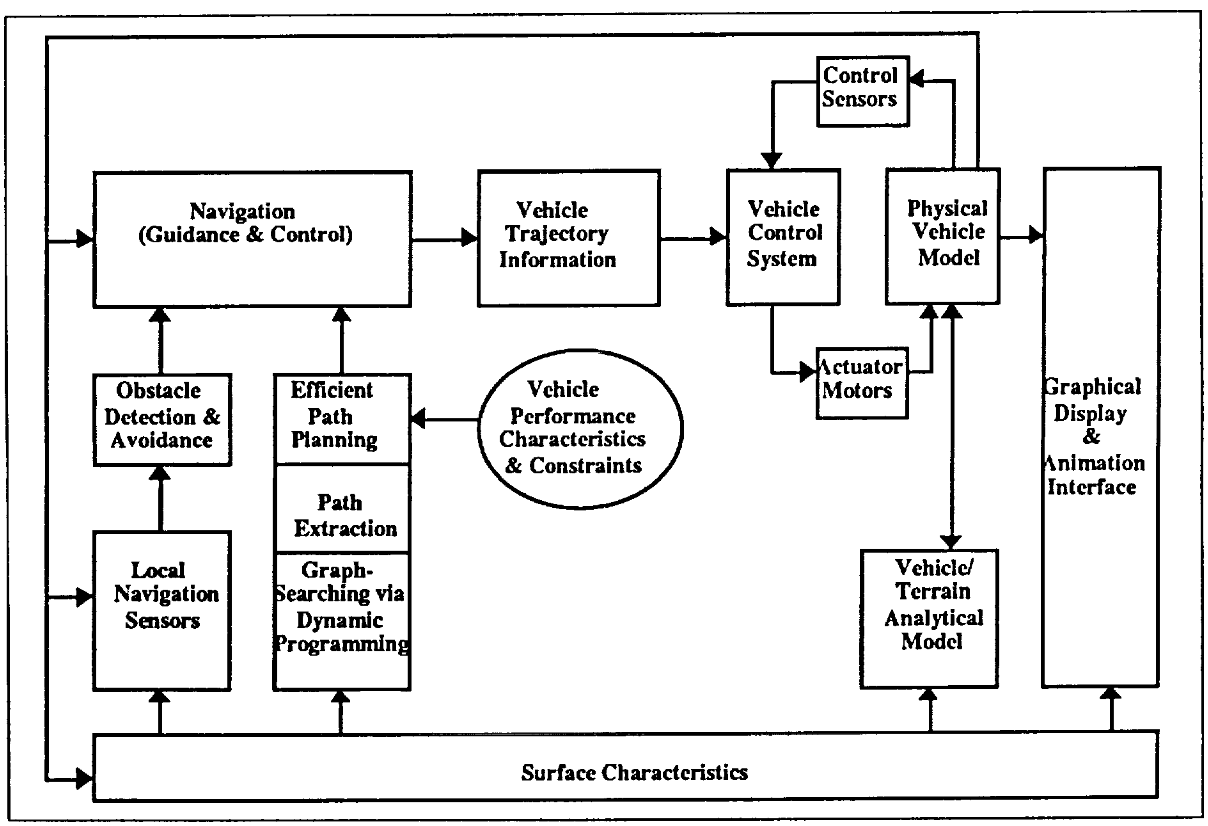


Fig. 25.1 Block diagram of the major components of a path-planning system

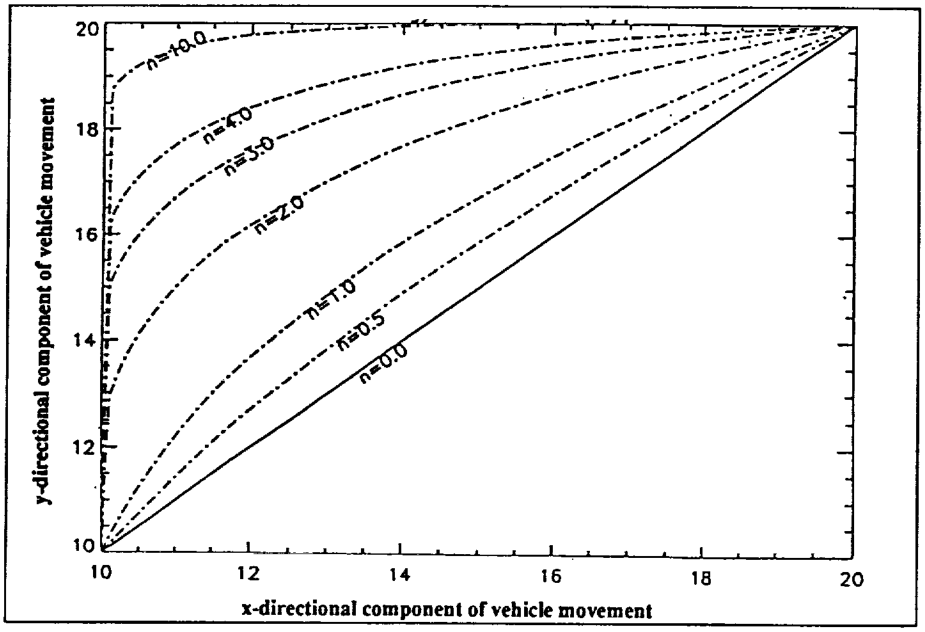
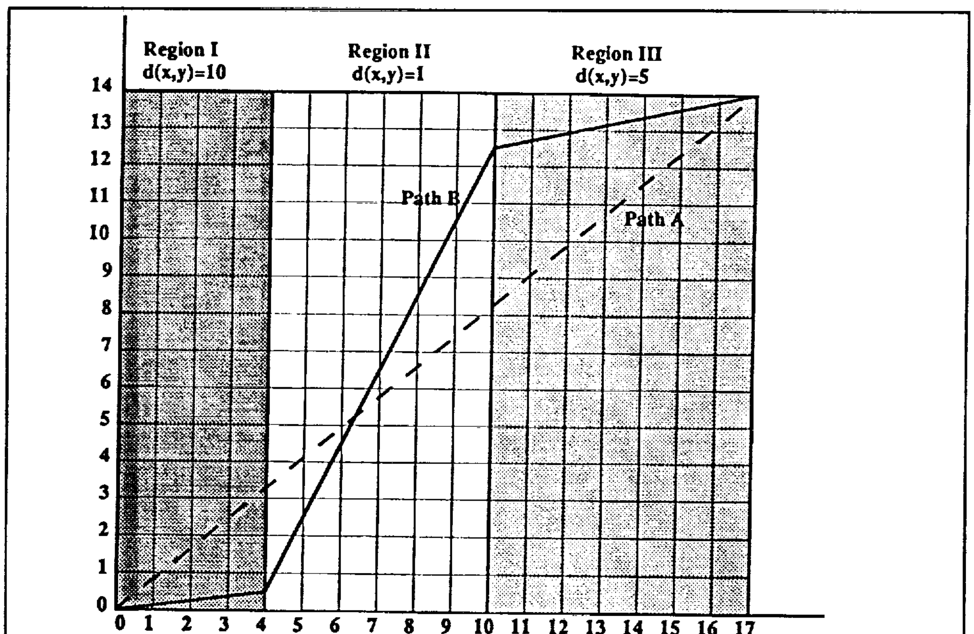


Fig. 25.2 Minimum energy paths for a drag function of the form d(x,y)=kx^n



Path A is the minimum distance route with an energy expenditure of 104.93. Path B is the minimum energy route with an expenditure of 87.48 which results in a 17.27% savings of expended energy.

Fig. 25.3 Comparison of energy expenditure between a minimum distance path and a minimum energy path

CONSTRUCTION SYSTEM SIMULATION AND OPTIMIZATION

George W. Morgenthaler, Richard Johnson

Due to a lack of time and personnel early in the traditional aerospace design process, phase-A lunar and Martian surface base designers cannot consider more than one or two alternative designs. Indeed, they often do not have time to consider methods of constructing the bases they are specifying. Rather than attempt to change the process, we are making it easier to include alternative construction strategies in evaluating technical merit and cost of phase-A designs.

This CSC construction system simulation and optimization project aims to explore the use of discrete-event and object-oriented simulation, memory-based and random-number-driven search methods, and multiple-objective utility functions for the rapid production of sensible and optimal construction strategies. Our experiments explore the use of operations simulation to analyze the performance of alternative teams of construction machinery. These alternative teams of machinery are selected from the pool of all possible teams with the aid of the search strategies. The multiple-objective utility functions drive the use of the search strategies to produce near-optimal construction systems for the base designers.

Our past operations simulation models have given us specific answers to our questions about construction logistics support, and reliability or time to complete construction tasks. Our simulation of logistics model (SIMLOG) showed us that space transportation system ground facilities were not capable of supporting the construction of a specific Space Station Freedom design on time. Our simulation of orbital assembly (SIMORB) model showed that we can simulate on-orbit assembly of Space Station Freedom trusses, using knowledge gained in underwater 0-g simulation test facilities and space-based experiments, to determine the likelihood of completing this kind of assembly successfully and on time. Our simulation of First Mars Outpost assembly (SIMFMO) model showed that we can trade two First Mars Outpost construction teams off against one another, using a process flow simulation to generate their expected times to successfully complete a 100-day construction mission.

Our work in determining the constructability of base designs has led to a standard representation of the construction process. Given a base architecture from the design team, it is possible to generate a set of required construction tasks for building the base. We have produced a standard set of generic construction tasks (Figure 26.1), which can be applied to base elements, prepared surfaces, and construction machinery. The tasks for an example base, the CSC First Mars Outpost, are presented in Figure 26.2. Using high-level tasks like those in Figure 26.1 pushes the "knowledge" about constructor capabilities down into the constructors themselves. This appears to be better than using detailed tasks and relying on the optimization engine to keep track of everything, leading to quicker and more flexible optimization of the construction process.

Combining the past simulation and optimization models and our representation of the construction process lets us apply object-oriented simulations to determine how well proposed construction systems perform. The simulations are fed with the tasks required and the construction machinery assigned to perform them. In the future, we will be using memory-based or random-number-based search methods to drive multiple-objective optimization of the simulated construction strategies (Figure 26.3).

TRANSPORT	SURVEY	EXCAVATE	EMPLACE	DEPLOY	ASSEMBLE
<part> from initial *<location>* to final *<location>*	*<location>*|*<area>*	*<location>*|*<area>* from initial *<topography>* to final *<topography>*	*<part>* in *<orientation>* at *<location>* [with *<precision>*]	*<part>* at *<location>*|*<area>*	*<part>* [and *<part>* [...]] into new *<part>* at *<location>*

Fig. 26.1 Generic construction tasks (expressed as messages passed to constructors)

TRANSPORT	rover-dozer	from hab-lander	to surface
SURVEY	tween-lander-road		
EXCAVATE	tween-lander-road	from raw-state	to road-surface
SURVEY	PVA-site		
EXCAVATE	PVA-site	from raw-state	to clear-level-suface
TRANSPORT	PVA	from hab-lander	to PVA-site
EMPLACE	PVA	in sun-pointing-position	at PVA-site
DEPLOY	PVA	at PVA-site	
ASSEMBLE	PVA-cable	and PVA	
ASSEMBLE	PVA-cable	and lander2	
SURVEY	entire-surrounding-area		
SURVEY	SP-100-site		
SURVEY	landing-pad		
EXCAVATE	landing-pad	from raw-state	to clear-level-surface
EMPLACE	landing-beacons	in ...	at landing-pad

Fig. 26.2 Partial list of First Mars Outpost construction tasks

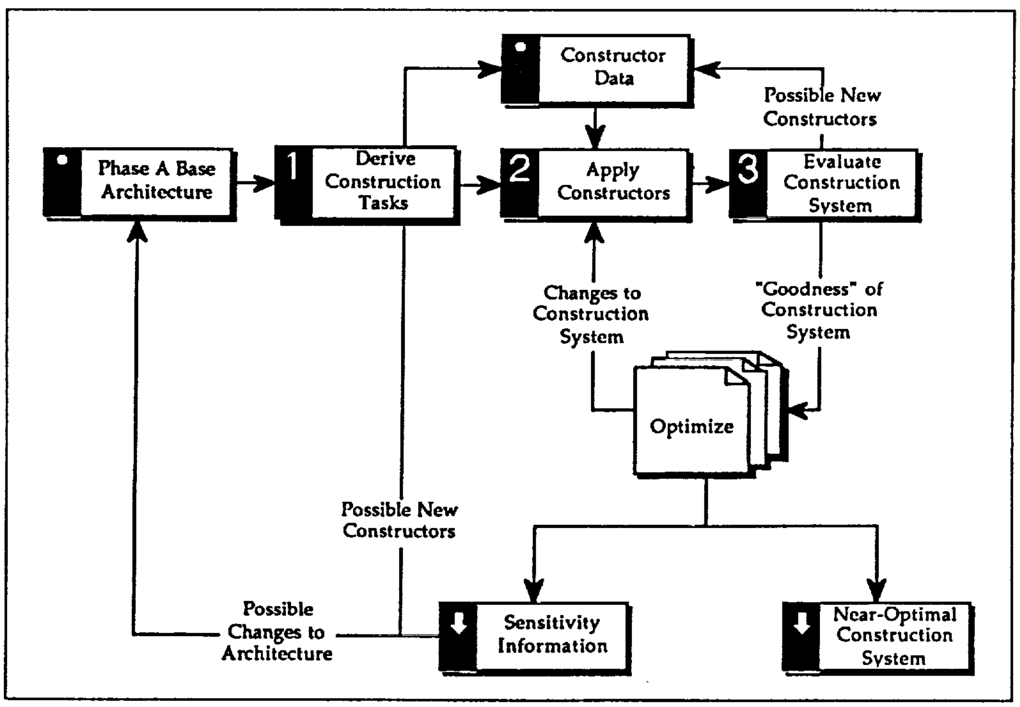


Fig. 26.3 Strategy for construction system optimization

EDUCATIONAL PROGRESS

GRADUATE STUDENTS

During the past year, nine CSC students received the MS degree and four CSC students received the PhD. They are listed below.

MASTER OF SCIENCE DEGREE

December 1992
John Happel
Jane Pavlich
Erik Swensen

May 1993
Alison Alderete
Gregory Hayman
Paul Labys
Ashok Srivastava
David Vandenbelt

August 1993
Del Shannon

DOCTOR OF PHILOSOPHY DEGREE

December 1992
Brian Reisenauer

May 1993
Philip Good

August 1993
François Hemez
Paul Stern

UNDERGRADUATE STUDENTS AND HOURLY ASSISTANTS

This year the Center had five undergraduate and three graduate hourly assistants who worked with CSC faculty, staff and students on Center research projects. Their names are listed below. These hourly assistants are an important part of the Center's program; through their work they receive exposure to the Center's goals and its ongoing research.

UNDERGRADUATE HOURLY ASSISTANTS
Cynthia Bridge
Shannon Gaydos
Stephanie Gow
Aneta Lewandowska
Andy Wobido

GRADUATE HOURLY ASSISTANTS
Kevin Gifford
Jane Pavlich
Erik Swensen

MODIFIED COURSES

During the past year CSC faculty have continued to modify existing courses to include instructional materials on space construction, further impacting engineering education at the University of Colorado with space construction research results.

ORGANIZATION

PERSONNEL — RESEARCH

In the current program period the Center's research continues in three major areas, a) spacecraft structures, b) spacecraft operations and controls, and c) regolith and surface systems. The names of personnel involved in each of the three areas during this program period are listed below. *Asterisks indicate personnel no longer with the project as of September 30, 1993 (because of graduation or for other reasons).*

The Center's research is conducted by its faculty, research personnel and students, with guidance and direction from the Director and the Executive Committee (see Personnel—Administration, p. 76). Weekly technical meetings are the forum for internal reporting on progress on the Center's research tasks. At these meetings students, research professionals and faculty share results and engage in dialogue which guides future efforts.

As of September 30, 1993 the Center's research personnel included 13 faculty members, five postdoctoral research associates (four part-time), two part-time researchers, three professional research assistants and 30 graduate and undergraduate students. Interaction between personnel engaged in various research projects is good and continues to build.

SPACECRAFT STRUCTURES

Faculty:	Charbel Farhat	
	Carlos Felippa	
	Martin M. Mikulas, Jr.	
	K.C. Park	
	Lee D. Peterson	
Post-Docs:	Gyula Greschik	
	François Hemez	
	*Li-Farn Yang	
Students:	*Alison Alderete	Graduate Research Assistant and GEM Fellow
	Scott Alexander	Graduate Research Assistant
	Gregory Brown	Graduate Research Assistant
	Steve Bullock	Graduate Research Assistant
	Scott Doebling	Graduate Student
	Shannon Gaydos	Undergraduate Hourly Assistant

Jeffery Goss	Graduate Student, NASA Fellow
Stephanie Gow	Undergraduate Student
M. Roman Hachkowski	Graduate Research Assistant
*Gregory Hayman	Graduate Research Assistant
François Hemez	Graduate Research Assistant
Jason Hinkle	Undergraduate Student; Graduate Research Assistant
Spencer Reeder	Graduate Student
*Paul Stern	Graduate Research Assistant
Timothy Straube	Graduate Research Assistant
*Erik Swensen	Graduate Hourly Assistant
Robert Taylor	Graduate Student, NASA Fellow
Gregory Thorwald	Graduate Research Assistant
Peter Withnell	Graduate Student
Andy Wobido	Undergraduate Student

SPACECRAFT OPERATIONS AND CONTROL

Faculty:	*James Avery	
	Penina Axelrad	
	Mark Balas	
	Dale Lawrence	
	Renjeng Su	
Post-Docs:	Jim Chapel	
	Noureddine Kermiche	
Researchers:	François Padieu	
	Jane Pavlich	
Students:	*Philip Good	Graduate Research Assistant
	Christopher Grasso	Graduate Research Assistant
	Timothy Holden	Graduate Research Assistant
	*Paul Labys	Graduate Student; DoED Fellow
	Aneta Lewandowska	Undergraduate Hourly Assistant
	Michael Malone	Graduate Research Assistant; Graduate Student
	Jane Pavlich	Graduate Research Assistant; Graduate Hourly Assistant
	Lawrence Robertson	Graduate Research Assistant
	Jay St. Pierre	Graduate Research Assistant
	Ashok Srivastava	Graduate Student; DoED Fellow
	Roger Toennis	Graduate Research Assistant
	Christopher Steffen	Graduate Research Assistant

REGOLITH AND SURFACE SYSTEMS

Faculty:	Frank Barnes, Professor	
	Hon-Yim Ko	
	*Wayne Rogers	
	Stein Sture	
	*Kaspar Willam	
Post-Docs:	Steven Jolly	
Students:	Cynthia Bridge	Undergraduate Hourly Assistant
	Kevin Gifford	Graduate Hourly Assistant
	*John Happel	Graduate Research Assistant
	Richard Johnson	Graduate Research Assistant
	J. Ledlie Klosky	Graduate Research Assistant
	*Michael Loucks	Graduate Research Assistant
	*Mark Nathan	Graduate Research Assistant
	Kendall Nii	Graduate Research Assistant
	*Delmer Shannon	Graduate Research Assistant
	Bela Szabo	Graduate Research Assistant

* *No longer with the Center as of September 30, 1993*

PERSONNEL — ADMINISTRATION

The Center is managed by the Director, with the assistance of the Executive Committee and the Assistant to the Director. The Director and the Executive Committee (composed of members of the faculty appointed by the Director) meet weekly to determine policy, budget matters and research directions. They also make decisions which govern the Center's daily operations.

The Assistant to the Director oversees the fiscal and reporting functions of the Center and its administrative operations. The Office Assistant/Symposium Coordinator serves as secretary, makes logistical arrangements for the Center's annual symposium, and in addition manages the Center's administrative and equipment databases and library, and provides office assistance including purchase processing and tracking.

The Laboratory Engineer/Technician assists students and faculty in laboratory design and fabrication. The Engineering Manager oversees the technical engineering aspects of the Center's experimental laboratory projects. The Staff Assistant provides part-time clerical and administrative assistance to a number of Center faculty.

Director:	Renjeng Su
Executive Committee:	Charbel Farhat Martin M. Mikulas, Jr. George W. Morgenthaler Stein Sture Renjeng Su
Assistant to the Director:	Carol Osborne
Professional Research Assistants:	Lisa Block, Office Assistant and Symposium Coordinator Jim Kastengren, Laboratory Engineer and Technician Walter Lund, Engineering Manager
Staff Assistant:	Catharine Moser

BUDGET

The Center is funded by National Aeronautics and Space Administration Grant NAGW-1388, which is renewed annually. The University of Colorado provides matching funds. In addition, the McDonnell Douglas Foundation has generously contributed annual gifts to the Center. A summary of funding to date follows.

FUNDING TO DATE

Period	Amount
NASA, Program Period 1 (July 1, 1988 - February 28, 1989)	449,507
NASA, Program Period 2 (March 1, 1989 - February 28, 1990)	1,414,168
NASA, Program Period 3 (March 1, 1990 - February 28, 1991)	1,688,511
NASA, Program Period 4 (March 1, 1991 - October 31, 1991)	1,291,957
NASA, Program Period 5 (November 1, 1991 - October 31, 1992)	1,781,399
NASA, Program Period 6 (November 1, 1992 - October 31, 1993)	1,530,000
Subtotal	8,205,542
University of Colorado Matching Funds, FY 1988-1989	100,000
University of Colorado Matching Funds, FY 1989-1990	100,000
University of Colorado Matching Funds, FY 1990-1991	100,000
University of Colorado Matching Funds, FY 1991-1992	100,000
University of Colorado Matching Funds, FY 1992-1993	100,000
University of Colorado Matching Funds, FY 1992-1993	100,000
Subtotal	600,000
McDonnell Douglas Foundation Gifts, 1989-1992	18,500
Total	$8,824,042

Funding for Program Period Six, November 1, 1992 through October 31, 1993, is summarized below.

PERIOD SIX FUNDING

	NASA	UC Matching
Salaries and Wages	746,270	
Fringe Benefits	91,331	
Computer Costs	18,600	15,000
Materials, Supplies and Services	37,275	35,000
Travel	49,700	0
Capital Equipment	78,000	50,000
Tuition	98,543	
Indirect Costs	410,281	
Total	$1,530,000	$100,000

PUBLICATIONS

CSC students defended the theses listed below during the period October 1992 to September 1993. The CSC-sponsored journal articles listed were either submitted for publication, in press, or published during the period October 1, 1992 to September 30, 1993. CSC researchers presented the listed conference papers at technical meetings during the same period. (The "CSCR" number for a paper or thesis is its number in the Center for Space Construction report series.)

DISSERTATIONS AND THESES

Reisenauer, Brian Thomas, "Decentralized Control of Flexible, Multibody Systems", PhD Dissertation, Department of Aerospace Engineering Sciences, University of Colorado, October 1992

Happel, John Amin, "The Design of Lunar Structures Using Indigenous Construction Materials", Master's Thesis, Department of Civil, Environmental and Architectural Engineering, University of Colorado, November 1992

Shannon, Delmer Allen, "Density Evaluation of Lunar Regolith", Master's Thesis, Department of Civil, Environmental and Architectural Engineering, University of Colorado, July 1993

Hemez, François M., "Theoretical and Experimental Correlation Between Finite Element Models and Modal Tests in the Context of Large Flexible Space Structures", PhD Dissertation, Department of Aerospace Engineering Sciences, University of Colorado, July 1993

Stern, Paul R., "Two Unconditionally Stable Staggered Numerical Procedures to Solve the Coupled Thermoelastic Problem", PhD Dissertation, Department of Aerospace Engineering Sciences, University of Colorado, August 1993

JOURNAL ARTICLES

Crivelli, Luis A. and Carlos A. Felippa, "A Three-Dimensional Non-Linear Timoshenko Beam Based on the Core-Congruential Formulation", International Journal for Numerical Methods in Engineering, Vol. 36, 1993, CSCR.93.18

Farhat, Charbel, Luis Crivelli and F.X. Roux, "Extending Substructure Based Iterative Solvers to Multiple Load and Repeated Analyses", Journal of Computational Methods in Applied Mechanics (in press)

Farhat, Charbel and M. Geradin, "On a Component Mode Synthesis Method and its Application to Incompatible Substructures", Computers and Structures (in press)

Farhat, Charbel and M. Geradin, "On the Deployment of Large Space Flexible Structures with Dissipative Joints", International Journal for Numerical Methods in Engineering (in press)

Farhat, Charbel and François Hemez, "Updating Finite Element Dynamic Models Using an Element-by-Element Sensitivity Methodology", AIAA Journal, Vol. 31, No. 9, pp. 1702-1711, September 1993, CSCR.93.27

Farhat, Charbel and F.X. Roux, "Regularization of the Method of Finite Element Tearing and Interconnecting", SIAM Journal

Hemez, François and Charbel Farhat, "Assessment of Structural Damage via a Finite Element Model Updating Methodology", Modal Analysis - International Journal of Analytical and Experimental Modal Analysis (submitted)

Jolly, Steven D., "Dynamic Construction Activities Model (DYCAM) 3.0: A Knowledge-Based Expert System Tool for Conceptual Design", AIAA 93-0955, AIAA Journal of Spacecraft and Rockets (submitted), CSCR.93.01

Jolly, Steven D. and Francisco J. Cestero, "Dynamic Construction Activities Model (DYCAM): Planning and Conceptual Design, Interactive Partners for Spacecraft Design", Journal of Architecture and Planning Research (in press), December 1993, CSCR.92.34

Jolly, Steve D., John Happel and Stein Sture, "Design and Construction of a Lunar Outpost", Journal of Aerospace Engineering (in press), ASCE, CSCR.93.22

Lawrence, Dale A., "Stability and Transparency in Bilateral Teleoperation", Transactions on Robotics and Automation (in press), CSCR.93.25

Macari, Emir, Kenneth Runesson and Stein Sture, "Prediction of the Response of Granular Materials at Low Effective Stress Levels", Journal of Geotechnical Engineering (in press)

Park, K.C. and J.C. Chiou, "A Discrete Momentum-Conserving Explicit Algorithm for Multibody Dynamics Analysis", AIAA 92-2089, International Journal for Numerical Methods in Engineering, Vol. 36, pp. 1071-1083, 1993, CSCR.92.13

Peric, Dunja, Kenneth Runesson and Stein Sture, "Prediction of Plastic Localization Using the MRS-Lade Model", Journal of Geotechnical Engineering, ASCE, Vol. 119, No. 4, April 1993, CSCR.92.03

Perkins, Steve, Stein Sture, Hon-Yim Ko and Christian Dialer, "Modellierung von Tragwerken aus Regolith (Mondgestein) mittels Zentrifugenversuch", Journal Bautechnik, Vol. 69, No. 11, pp. 644-640, November 1992, CSCR.92.14

Stankowski, Thomas, Kenneth Runesson and Stein Sture, "Fracture and Slip of Interfaces in Cementitious Composites. I: Characterization", Journal of Engineering Mechanics, ACSE, Vol. 119, No. 2, pp. 292-314, February 1993, CSCR.93.15

Stankowski, Thomas, Kenneth Runesson and Stein Sture, "Fracture and Slip of Interfaces in Cementitious Composites. II: Implementation", Journal of Engineering Mechanics, ACSE, Vol. 119, No. 2, pp. 315-327, February 1993, CSCR.93.16

Yang, Li-Farn, "An Alternative Variable Transformation for Simulation of Multibody Dynamic Systems", AIAA Journal of Guidance, Control and Dynamics (submitted), CSCR.93.19

Yang, Li-Farn, Meng-Sang Chew and Jer-Nan Juang, "Concurrent Mechanism and Control Design for the Slewing of Flexible Space Structures", ASME Journal of Mechanical Design (in press), est. October 1993, CSCR.93.14

Yang, Li-Farn and Martin M. Mikulas, Jr., "Mechanism Synthesis and 2-D Control Designs of An Active Three Cable Crane", AIAA A9388, Journal of Spacecraft and Rockets (in press), September 1993, CSCR.93.05

Yang, Li-Farn, Martin M. Mikulas, Jr., K. C. Park and Renjeng Su, "Slewing Maneuvers and Vibration Control of Space Structures by Feedforward/Feedback Moment-Gyro Controls", AIAA 93-1675, ASME Journal of Dynamic Systems, Measurement, and Control (in press), est. February 1994, CSCR.93.10

CONFERENCE PAPERS

Doebling, Scott W., Kenneth F. Alvin and Lee D. Peterson, "Limitations of State-Space System Identification Algorithms for Structures with High Modal Density", to be presented at International Modal Analysis Conference, Honolulu, Hawaii, January 31 - February 3, 1994, CSCR.93.26

Doebling, S. W., F. W. Hemez, M. S. Barlow, L. D. Peterson, C. Farhat, "Damage Detection in a Suspended Scale Model Truss Via Model Update", presented at the 11th International Modal Analysis Conference (IMAC), Kissimmee, Florida, February 1-4, 1993, CSCR.93.02

Doebling, Scott W., François M. Hemez, M.S. Barlow, Lee D. Peterson and Charbel Farhat, "Selection of Experimental Modal Data Sets for Damage Detection Via Model Update", presented

at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.08

Farhat, Charbel and Luis Crivelli, "On the Spectral Stability of Time Integration Algorithms for a Class of Constrained Dynamics Problems", AIAA 93-1306, presented at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.07

Farhat, Charbel and François Hemez, "An Energy Based Optimum Sensor Placement Criterion and its Application to Structural Damage Detection", to be presented at 12th International Modal Analysis Conference (IMAC), Honolulu, Hawaii, January 31 - February 3, 1994, CSCR.93.28

Felippa, Carlos A., Luis A. Crivelli, and David Vandenbelt, "Configuration-Shape-Size Optimization of Space Structures", presented at Advanced Space Structures, ASME Winter Annual Meeting, Anaheim, California, November 9-13, 1992, CSCR.92.24

Felippa, Carlos A., Luis A. Crivelli, and David Vandenbelt, "Configuration-Shape-Size Optimization of Space Structures by Material Redistribution", presented at AIAA/ASME/ASCE/AHS 34th Structures, Structural Dynamics and Materials Conference, La Jolla, California, April 19-21, 1993, CSCR.93.17

Gifford, Kevin K. and George W. Morgenthaler, "Minimum Energy Vehicle Path Planning for the Martian Surface", presented at the Case for Mars V Conference, Boulder, Colorado, May 26-29, 1993, CSCR.93.24

Good, Philip G. and Dale A. Lawrence, "Decentralized Interaction Control for Flexible Structures", presented at American Control Conference, San Francisco, California, June 8-10, 1993, CSCR.93.21

Hemez, François M. and Charbel Farhat, "Comparing Mode Shape Expansion Methods for Test-Analysis Correlation", to be presented at 12th International Modal Analysis Conference (IMAC), Honolulu, Hawaii, January 31 - February 3, 1994, CSCR.93.29

Hemez, François M. and Charbel Farhat, "Locating and Identifying Structural Damage Using a Sensitivity-Based Updating Methodology", AIAA 93-1608, presented at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.06

Hemez, François M. and Charbel Farhat, "Theoretical and Experimental Study of the Correlation Between Finite Element Models and Modal Tests for Large and Flexible Space Structures" (in French), presented at the 1993 CSMA/GAMNI/INRIA National Conference in Structural Design, Giens, France, May 11-14, 1993, CSCR.93.04

Hinkle, Jason and Steven J. Bullock, "The Sensitivity of Identified Modal Parameters to Sensor Placement Errors and Construction Tolerances", presented at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.11

Kermiche, Noureddine and Renjeng Su, "A Two-Stage Training Method For Feedforward Networks", presented at World Congress of Neural Networks 1993, Portland, Oregon, July 11-15, 1993, CSCR.93.03

Mikulas, Martin M. Jr., B.K. Wada and Charbel Farhat, "Initially Deformed Truss Geometries for Improving the Adaptive Performance of Truss Structures", presented at the Third International Conference on Adaptive Structures, San Diego, California, November 9-11, 1992, CSCR.92.36

Mikulas, Martin M. and Peter R. Withnell, "Construction Concepts for Segmented Precision Reflectors", AIAA 93-1461, presented at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.12

Nathan, Mark P., Frank Barnes, Stein Sture, Hon-Yim Ko and Walter Lund, "A Comparison of the Efficiencies of a New Class of Lunar Excavation Tools", presented at ASME Winter Annual Meeting, Anaheim, California, November 9-13, 1992, CSCR.92.32

Peterson, Lee D., K.F. Alvin, Scott W. Doebling, K. C. Park, "Damage Detection Using Experimentally Measured Mass and Stiffness Matrices", presented at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.09

Robertson III, Lawrence and Mark J. Balas, "Stable Assembly of Active Structures Using Perturbation Methods", presented at IEEE Conference on Aerospace Control Systems, Westlake Village, California, May 25-27, 1993, CSCR.93.20

Schipper, John and Mark Balas, "Active Control of Persistent Disturbances in a Flexible Robot Manipulator", presented at ASME Winter Annual Meeting/Symposium on Active Control of Noise and Vibration, Anaheim, California, November 11-13, 1992, CSCR.92.18

Sture, Stein, Steve D. Jolly and John Happel, "A Near-Term, Long-Duration Lunar Outpost Design", to be presented at Space 94 Conference, Albuquerque, New Mexico, 1994, CSCR.93.23

Taylor, Robert M., Martin M. Mikulas, Jr. and John M. Hedgepeth, "A Two Cable, Six Link Boom Crane for Lunar Construction", AIAA 93-1340, presented at AIAA/ASME/ASCE/AMS 34th Structures, Dynamics and Materials Conference, La Jolla, California, April 19-22, 1993, CSCR.93.13

CONFERENCES AND MEETINGS

During the period October 1, 1992 to September 30, 1993, Center for Space Construction personnel attended the following conferences and technical meetings.

AAS Guidance and Control Conference, Keystone CO, February 1993 (not previously reported).

RPI NASA-SERC Annual Symposium, Troy NY, October 1992.

NASA/DOD Flight Experiments Technical Interchange Meeting, Monterey CA, October 1992.

ASME Winter Annual Meeting, Anaheim CA, November 1992.

IEEE 31st Conference on Decision and Control, Tucson AZ, December 1992.

International Modal Analysis Conference, Orlando FL, February 1993.

University of Arizona NASA-SERC Annual Symposium, Tucson AZ, February 1993.

AIAA Aerospace Design Conference, Irvine CA, February 1993.

AIAA 34th Structures, Structural Dynamics and Materials Conference, La Jolla CA, April 1993.

Annual University Space Engineering Research Centers Directors' Meeting at NASA Headquarters, Washington DC, May 1993.

AIAA/SOLE 5th Annual Meeting, Huntsville AL, May 1993.

Conference on Aerospace Control Systems, Los Angeles CA, May 1993.

IEEE International Conference on Robotics and Automation, Atlanta GA, May 9113.

SES/ASME/ASCE Joint Mechanics Meeting, Charlottesville VA, June 1993.

NSF Coordination Conference, Ann Arbor MI, June 1993.

American Control Conference, San Francisco CA, June 1993.

DOE 4th Industry/University/Laboratory Forum on Robotics for Environmental Restoration and Waste Management, Albuquerque NM, July 1993.

NASA-OACT Small Spacecraft Technology Workshop, Pasadena CA, September 1993.

ASME Bi-Annual Vibration Conference, Albuquerque NM, September 1993.

AIAA/USU 7th Conference on Small Satellites, Logan UT, September 1993.